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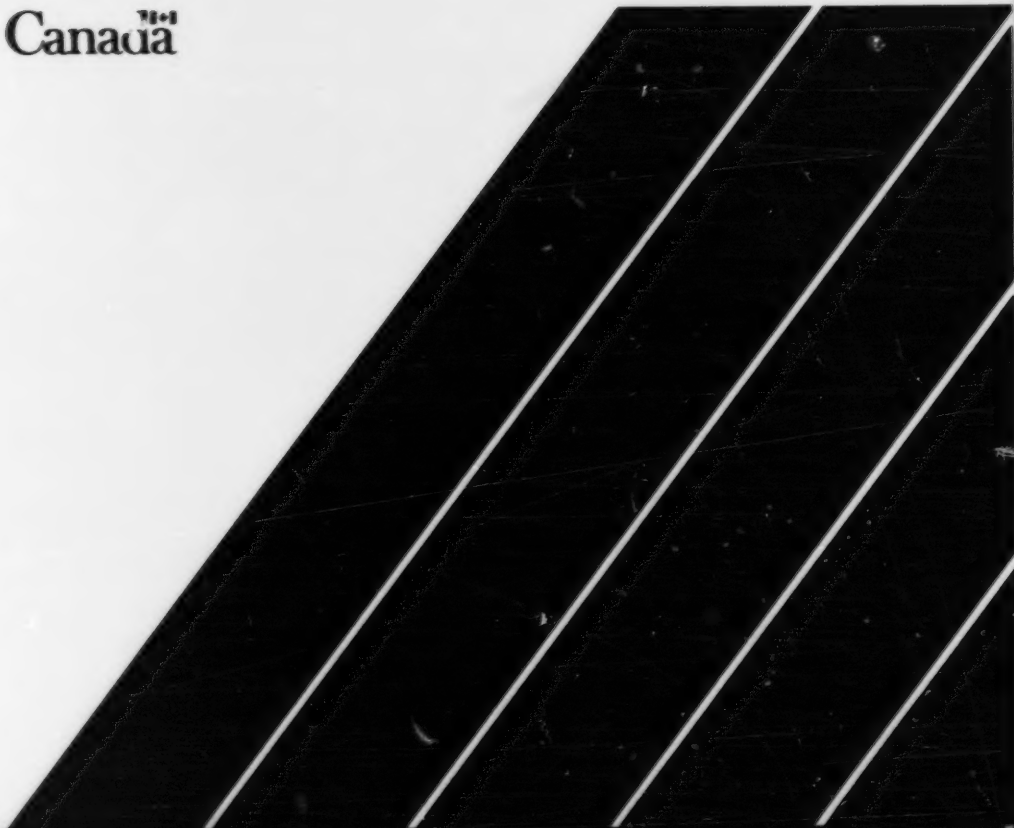
LABORATORY MEASUREMENTS OF THE HYDROFRACTURING TENSILE STRENGTH OF TWO LARGE URL ROCK SAMPLES

J.S.O. Lau, R. Jackson and B. Gorski

March 1991

Mining Research Laboratories
Divisional Report MRL 91-035(TR)

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ADDITIONAL

LABORATORY MEASUREMENTS OF THE HYDROFRACTURING TENSILE STRENGTH OF TWO LARGE URL ROCK SAMPLES

by

J.S.O. Lau¹, R. Jackson² and B. Gorski³

ABSTRACT

In support of AECL Research's hydrofracturing testing program for the measurement of in situ stresses at the Underground Research Laboratory (URL), an experiment was designed and conducted at the Canada Centre for Mineral and Energy Technology to determine the large-scale laboratory hydrofracturing tensile strength, T_{lab} , of two 600-mm-diameter core samples of Lac du Bonnet grey granite obtained from the 240 level of the URL. A subvertical hydrofracture was created in one specimen which had microcracks parallel to the core axis, and T_{lab} was found to be 7.40 MPa. A subhorizontal hydrofracture was created in the other specimen which had microcracks perpendicular to the core axis. It is suggested that the orientation of the hydrofracture could be influenced by the orientation of microcracks present in a specimen or in situ. The results, in comparison with the tensile strengths obtained using other test methods, indicate that the tensile strength decreases with increasing specimen size.

Keywords: hydrofracturing, end plugs, strain gauges, hydraulic pressure, stress, strain, tensile strength, microcracks, scale effect

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MESURES EN LABORATOIRE DE LA RÉSISTANCE À LA TRACTION DE FRACTURATION HYDRAULIQUE DE DEUX GROS ÉCHANTILLONS DE ROCHE DU LRS

par

J.S.O. Lau¹, R. Jackson² et B. Gorski³

RÉSUMÉ

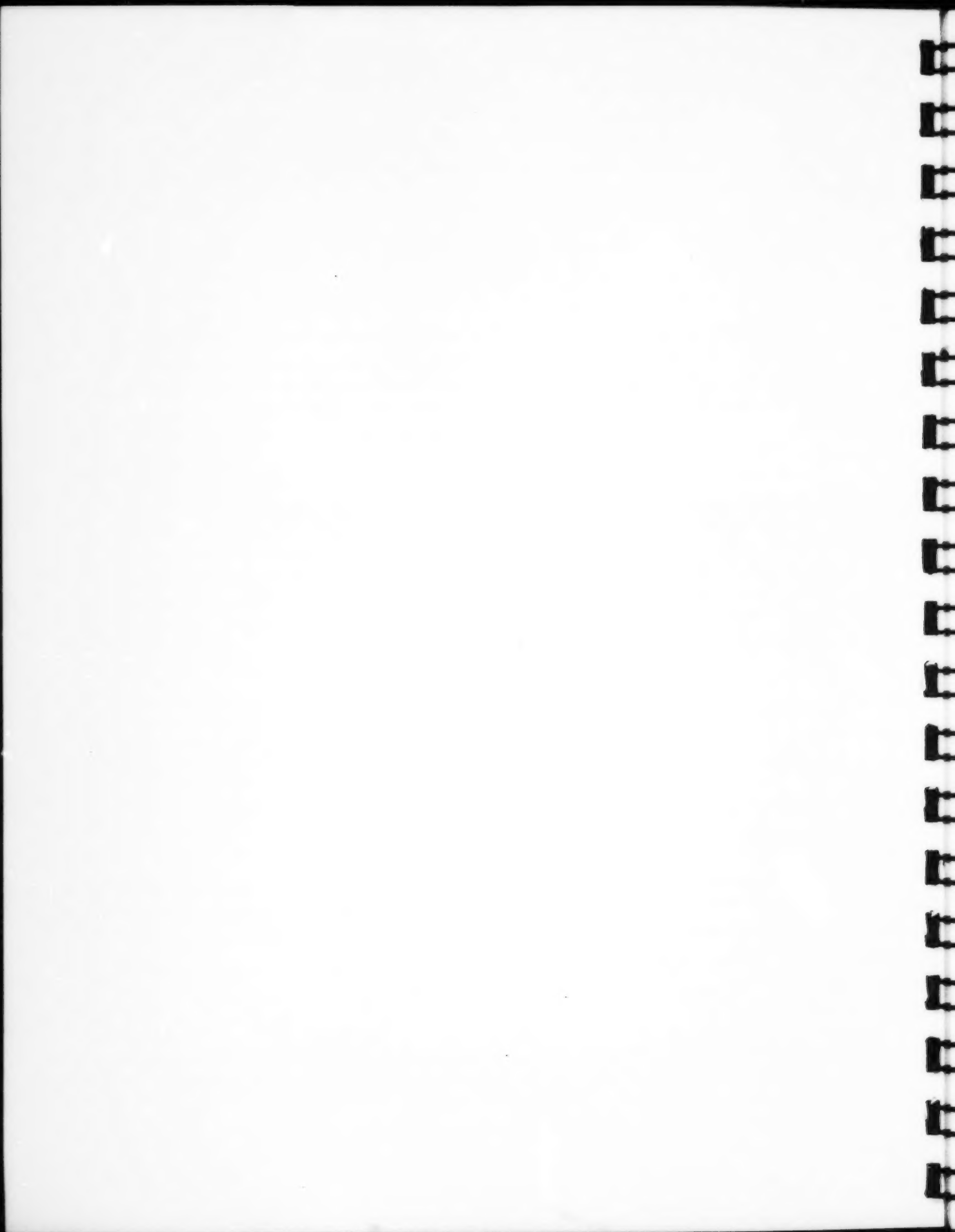
En appui au programme d'essai sur la fracturation hydraulique d'EACL Recherche destiné à la mesure des contraintes in situ au Laboratoire de recherche souterrain (LRS), une expérience a été conçue et réalisée au Centre canadien de la technologie des minéraux et de l'énergie en vue de déterminer la résistance à la traction de fracturation hydraulique en laboratoire à grande échelle. T_{lab} , de deux carottes de granite gris de Lac du Bonnet de 600 mm de diamètre provenant du niveau 240 du LRS. Une fracture hydraulique subverticale a été créée dans un échantillon, qui contenait des microfissures parallèles à l'axe et la valeur obtenue pour T_{lab} était de 7.40 MPa. Une fracture hydraulique subhorizontale a été créée dans l'autre échantillon, qui contenait des microfissures perpendiculaires à l'axe. On a supposé que l'orientation des microfissures présentes dans un échantillon ou in situ pouvait avoir une influence sur l'orientation de la fracture hydraulique. Les résultats, par comparaison avec ceux obtenus au moyen d'autres méthodes d'essai, montrent que la résistance à la traction diminue lorsque la taille de l'échantillon augmente.

Mots-clés: fracturation hydraulique, bouchons d'extrémité, jauges de déformation, pression hydraulique, contrainte, déformation, résistance à la traction, microfissures, effet d'échelle

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INTRODUCTION

AECL Research is conducting geotechnical research at its Underground Research Laboratory (URL) in the Lac du Bonnet Batholith, located 100 km northeast of Winnipeg, Manitoba. The geotechnical research is part of the Canadian Nuclear Fuel Waste Management Program (CNFWMP) to assess the concept of nuclear fuel waste disposal in a vault deep in a plutonic rock mass. One issue concerns the in situ stress condition in a plutonic rock body and whether the stresses induced around an excavation in such a body can be understood. The stresses affect not only the stability of the excavation, but also the development of damaged zones around the excavation, which are potential pathways for radionuclide leakage from the vault.

A comprehensive measurement program has been underway since 1982 to characterize the in situ stress state at the URL (Simmons and Soonawala, 1982; Lang et al., 1986; Martin, 1990; Martin et al., 1990). Methodologies have included hydrofracturing, overcoring, convergence and under-excavation.

Hydrofracturing, carried out in an unfractured section of a borehole, attempts to provide the maximum and minimum stresses in the plane perpendicular to the borehole axis. Owing to the rather illusive tensile strength parameter which is used in the calculation of the maximum stress, a laboratory testing program was initiated early in 1990 to simulate hydrofracturing tests in two 600-mm rock cores from the URL in order to obtain the large-scale laboratory hydrofracturing tensile strength values for the Lac du Bonnet grey granite. It was hoped that the results would provide values of tensile strength for the URL rock, which are more representative of field conditions than those obtained from small-scale laboratory tests. The results can also be used to determine what, if any, the effect of specimen size is on the tensile strength of the rock.

The program was conducted jointly by AECL Research and the Canada Centre for Mineral and Energy Technology (CANMET) at CANMET's Canadian Mine Technology Laboratory, Mining Research Laboratories in Ottawa. Queen's University also participated in this program by attempting to source locate and track crack initiation and propagation through ultrasonic imaging and acoustic emission monitoring on the specimens during the tests. Their observations and results will be presented in a separate report. This report describes the laboratory hydrofracturing test apparatus and procedure developed by CANMET, and presents and discusses the results obtained from the tests.

HYDROFRACTURING

The concepts involved in determining in situ stresses by the hydrofracturing method are well established and have been published by several authors (Haimson and Fairhurst, 1967; Haimson, 1973, 1978, 1980, 1981; Pine et al., 1983; Haimson et al., 1989; Ljunggren and Amadei, 1989; Matsunaga et al., 1989). In a typical hydrofracturing test, an unfractured section of a borehole is sealed off by means of inflatable packers. This isolated section is then hydraulically pressurized at a constant flow rate until the borehole wall ruptures and a hydrofracture is induced. The peak pressure at which the borehole ruptures is the breakdown pressure, P_c . The pressurization is then shut off, allowing the pressure to drop sufficiently for the hydrofracture to close. The pressure at which the induced hydrofracture closes is the shut-in pressure, P_s . Further pressurization cycles may be performed to obtain the fracture reopening pressure, P_r , and confirmatory values of P_s .

When vertical hydrofracturing occurs in a vertical borehole, the shut-in pressure is conventionally interpreted as equal to the minimum principal horizontal stress, S_h :

$$S_h = P_s \quad (1)$$

with the orientation of S_h perpendicular to the plane of the vertical hydrofracture. The maximum principal horizontal stress, S_H is determined as a function of the breakdown pressure, shut-in pressure, tensile strength T of the rock and pore water pressure P_o (Haimson et al., 1989):

$$P_c - P_o = T + 3(S_h - P_o) - (S_H - P_o) \quad (2)$$

The tensile strength of the rock is usually determined from laboratory tests and Equation 2 becomes:

$$P_c - P_o = T_{lab} + 3(S_h - P_o) - (S_H - P_o) \quad (3)$$

The values of T_{lab} can be obtained from laboratory hydrofracturing tests, Brazilian tests and direct tensile tests. Since the volume of rock influenced by an in situ hydrofracturing test is generally larger than that used on a laboratory scale, T_{lab} is expected to be greater than T . It is the objective of this testing program to simulate hydrofracturing in large specimens to determine values of T_{lab} which may be closer to the value of T in the field than those obtained from small-scale laboratory tests.

TEST SPECIMENS

The two 600-mm core specimens used in these laboratory hydrofracturing tests were supplied by AECL Research. One specimen was obtained from borehole 209-054-RST2 and the other from borehole 210-020-RST1, both drilled at the 240 level of the URL. The locations, orientations and dimensions of the specimens are shown in Table 1.

ROCK PROPERTIES

In general, the rock is a grey, medium- to coarse-grained granite, composed of approximately 30% K-feldspar, 30% plagioclase, 30% or slightly less quartz and 10% or slightly more mafic minerals, mainly biotite. However, a large quartz-rich pegmatite was observed at one end of Specimen 1 from borehole 209-054-RST2. Recent studies by Jackson (1988) and Martin (1990) showed that core samples taken below a depth of about 200 m at the URL contained stress-induced microcracks. It is therefore reasonable to believe that microcracks were present in these two specimens.

Three Brazilian tests, conducted on 45-mm core samples from borehole URL-5 (266 m depth) in the vicinity of the 240 level of the URL, yielded a mean tensile strength of 8.06 MPa for this rock (standard deviation (s.d.) = 0.93 MPa) (Annor and Jackson, 1987). The mean uniaxial mechanical properties, as well as, the uniaxial compressive strength of the intact rock material, σ_c , and the material constants m and s predicted by the Hoek and Brown failure criterion (Hoek and Brown, 1980) for samples obtained from boreholes 209-021-SV1 and 209-025-SV2 (Lau and Gorski, 1990) are listed below. These boreholes are located at the 240 level of the URL and can be considered representative of the rock used for the hydrofracturing program.

mean bulk density = 2.63 Mg/m³ (s.d. = 0.01 Mg/m³)

mean uniaxial compressive strength = 185.7 MPa (s.d. = 3.5 MPa)

mean 50% tangent Young's modulus = 65.52 GPa (s.d. = 1.12 GPa)

mean Poisson's ratio = 0.38 (s.d. = 0.16)

Hoek and Brown failure criterion: $\sigma_c = 203$ MPa, $m = 36.47$, $s = 1.0$

SPECIMEN PREPARATION

To prepare the specimen for the laboratory hydrofracturing test, a 101.6-mm-diameter borehole was drilled through the centre and parallel to the core axis of the cylindrical specimen, using a 12-inch Cincinnati drill press and special diamond impregnated thin-walled core barrels and extension shafts supplied by J.K.S. Boyles International. Twenty-six flat spots were ground on the surface of the specimen, including a ring of sixteen at mid-height and two rings of five near to the two ends of the specimen, for the installation of piezoelectric transducers. In order to record the deformation on the inside of the specimen during the hydrofracturing test, four strain gauge rosettes (axial and circumferential) were installed at mid-depth on the borehole walls at approximately 90° from one to the other. The strain gauges and the leads were waterproofed by coating with Dow Corning 730 RTV fluorosilicone sealant. Two diametrically opposed axial strain gauges and two diametrically opposed circumferential strain gauges were also mounted at mid-height on the surface of the specimen to record the deformation on the outside of the specimen.

TEST APPARATUS

In designing the laboratory hydrofracturing test apparatus, emphasis was placed on making it simple and cost effective because only two specimens would be tested. Instead of using inflatable packers which are costly to develop, the test interval was isolated by two end plugs (Fig. 1) made from mild steel in CANMET. The end plugs were sealed in place using a gypsum cement known as Hydrostone. One end plug was equipped with four Conax electrode plugs which allowed the passage of wiring from the strain gauge rosettes inside the borehole to the strain indicators outside the borehole. Two additional holes were provided in the end plug for deairing and water pressurization. The two end plugs were connected by a 19-mm diameter mild steel shaft. One end of the shaft was threaded directly to the first plug while the other end was secured to a hollow Enerpac jack attached to the outside of the second plug (Fig. 1). The jack was used to prevent tensile stresses from developing along the borehole walls as a result of pressure from the injection fluid on the end caps.

The pumping system was provided by the MTS 815 Rock Mechanics Test System, a computer-controlled, servo-hydraulic compression machine. The pore pressure and confining pressure intensifiers in the system are equipped with servo-valves and function generators, and can be ramped in the pressure-control or stroke-control mode using a

PDP 11/73 computer. The pore pressure intensifier was used to generate the hydraulic pressure for the hydrofracturing test, whereas, the confining pressure intensifier was used to supply compensating pressure to the Enerpac jack. A schematic layout of the apparatus is shown in Figure 2.

TEST PROCEDURE

The hydrofracturing test was conducted by filling the sealed borehole with water. The borehole and the Enerpac jack were connected to the pore pressure intensifier and the confining pressure intensifier respectively. The strain gauges on the outside of the specimen were connected to the MTS system through B & K type 1526 strain indicators, while the strain gauge rosettes on the inside were connected to an IBM PC equipped with a Scimetrix data acquisition system (Fig. 2). The IBM PC was also connected to the MTS system for the recording of the hydraulic pressure during the test. Twenty-six piezoelectric transducers were installed on the surface of the specimen by Queen's University to conduct ultrasonic imaging and acoustic emission monitoring.

Hydraulic pressure could be applied in either the pressure-control mode or the stroke-control mode. During the test, time, pressure and strains were recorded at intervals of 0.5 or 1 second by the two computers. Tomographic velocity scans were made before and after the test, and acoustic emissions were monitored during the test by Queen's University to detect crack initiation and propagation. Acoustic emissions were also recorded for about one hour after a hydrofracture had been created.

CALCULATIONS OF STRESSES

In these tests, the hollow cylindrical specimens can be treated as thick-walled cylinders subjected to an internal pressure. Equations developed by Seely and Smith (1967) for the analysis of stresses in a hollow cylinder under an internal pressure can therefore be used to calculate the stresses for these tests.

The tangential stress, σ_t , and radial stress, σ_r , at a point at any distance ρ from the central axis of a relatively long open-ended thick-walled cylinder, subjected to an internal pressure only, are given as follows:

$$\sigma_t = p_1 \frac{r_1^2}{r_2^2 - r_1^2} \left(\frac{r_2^2}{\rho^2} + 1 \right) \quad (5)$$

$$\sigma_r = p_1 \frac{r_1^2}{r_2^2 - r_1^2} \left(\frac{r_2^2}{\rho^2} - 1 \right) \quad (6)$$

where r_1 = inside radius of the cylinder
 r_2 = outside radius of the cylinder

The tangential stress is tensile and the radial stress is compressive. No pressure is applied in the longitudinal direction and therefore, there is no longitudinal stress. From Equations 5 and 6, it can be seen that σ_t is always greater than σ_r . The maximum value of the tangential stress, σ_{tmax} , occurs at the inner surface of the cylinder when ρ has its least value ($\rho = r_1$), and is found to be:

$$\sigma_{tmax} = p_1 \frac{r_2^2 + r_1^2}{r_2^2 - r_1^2} \quad (7)$$

or

$$\sigma_{tmax} = p_1 \left(\frac{w^2 + 1}{w^2 - 1} \right) \quad (8)$$

where w = ratio of r_2 to r_1 .

In the laboratory hydrofracturing test, the hydraulic pressure is p_1 . As p_1 increases in the hole, σ_{tmax} also increases. Since the porosity of the granite is very low (Katsube et al., 1985) and the test duration is short (less than one minute), the pore pressure that exists at the wall of the hole during hydrofracturing is negligible and can be assumed to be zero. Using the maximum tensile stress failure criterion, fracturing will occur at a point on the wall of the hole where σ_{tmax} is equal to or greater than the tensile strength of the rock, T_{lab} , and the fracture will extend along a plane normal to the direction of σ_{tmax} . Thus, T_{lab} can be related to p_1 through Equation 8:

$$T_{lab} = p_1 \left(\frac{w^2 + 1}{w^2 - 1} \right) \quad (9)$$

TEST RESULTS AND DISCUSSION

Results from these tests are presented in the forms of pressure-time records and strain-time records. No meaningful data was obtained from the strain gauge rosettes mounted on the inside of the specimen in any test, due to short circuits probably caused by pressurized water seeping through the sealant onto the strain gauges. Consequently, for each test, only the strain-time records for the two axial and the two circumferential strain gauges mounted on the outside of the specimen are presented in this report. These strains are denoted as axial strain numbers 1 and 2, and circumferential strain numbers 1 and 2.

SPECIMEN 1

The hydrofracturing test on Specimen 1 from borehole 209-054-RST2 started in the pressure-control mode. The hydraulic pressure was increased at a constant rate of 0.5 MPa/s (typical field rate). Figure 3 shows the pressure-time record and Figures 4 to 7 present the strain-time records. It can be seen that the pressure rose to 4.38 MPa, then dropped to 4.18 MPa, rose again and finally reached a maximum value of 6.16 MPa when the test had to be abruptly ended due to the leak at the contact between the granite and the pegmatite in the specimen. The strain-time records show that the axial strains decreased (shortening) and the circumferential strains increased (stretching) slightly during the test, but no hydrofracturing occurred.

The test was rerun in the stroke-control mode, at a constant rate of 0.5 mm/s (flow rate $\approx 3.28 \text{ cm}^3/\text{s}$). The pressure reached a value of 5.70 MPa and then started to drop (Fig. 8) due to the same leakoff problem. A small leak past one of the end plugs was also observed. Finally, the test had to be terminated due to the lack of hydraulic fluid. The strain-time records (Figs. 9-12) show that the two axial strains and one circumferential strain increased slightly, indicating that some microcracks in the specimen were opening and possibly taking water during the test. The other circumferential strain was found to decrease slightly.

The test was repeated in the pressure-control mode, at a higher pressure rate of 0.75 MPa/s in order to shorten the duration of the test to overcome the leakoff problem. The pressure-time curve (Fig. 13) shows that the pressure reached a maximum value of 7.00 MPa and then decayed rapidly to zero. At exactly the same time, the axial and circumferential strains also rose sharply and then dropped rapidly to zero (Figs. 14-17), with the exception of circumferential strain No. 1 which stabilized after the rise.

Rupture of the borehole wall occurred and a subvertical hydrofracture was created, splitting the specimen into two equal halves. The direction of the hydrofracture was subparallel to the core axis, measuring approximately 25° from the reference line on the core, in agreement with the theory of hydrofracturing. Figure 18 illustrates the trace of the hydrofracture on the surface of the core specimen as if the surface were split vertically along the reference line and laid out horizontally. The maximum pressure, p_1 , obtained in this test was used to calculate the hydrofracturing tensile strength of the specimen, T_{lab} , using Equation 9, and the value of T_{lab} was found to be 7.40 MPa.

SPECIMEN 2

The hydrofracturing test was conducted on Specimen 2 from borehole 210-020-RST1 first in stroke-control mode with 1 mm/s rate (flow rate $\approx 6.55 \text{ cm}^3/\text{s}$). The pressure-time record (Fig. 19) shows that the hydraulic pressure rose to 4.32 MPa, then dropped to 3.98 MPa, and then rose again to a peak value of 5.59 MPa. This was followed by another drop to 3.96 MPa and then a slight rise to 4.45 MPa, where the pressure stabilized. The axial strains and circumferential strain No. 2 were found to increase, but circumferential strain No. 1 decreased with increasing pressure up to the peak pressure and then stabilized (Figs. 20 to 23), indicating some microcracks were opening and taking water. Water leakage through a quartz-rich porous zone located at about 30 cm from one end of the specimen was observed during the test. No hydrofracturing occurred and finally the test had to be terminated due to the lack of hydraulic fluid.

The test was performed again with pressurization switched to the pressure-control mode. The hydraulic pressure was increased at a rate of 0.5 MPa/s. The pressure-time plot is shown in Figure 24 and the strain-time records are presented in Figures 25 to 28. The maximum pressure reached in this run was 6.27 MPa. The axial strains and circumferential strain No. 2 increased slightly while circumferential strain No. 1 changed very little during the test. At the maximum pressure, the leakage through the porous zone became copious, and the test had again to be terminated due to the lack of hydraulic fluid.

To solve the leakage problem, the end plug close to the porous zone was relocated to preclude the porous zone in the specimen. The test was then repeated with an increased pressure rate of 0.75 MPa/s. The pressure-time and strain-time records show that the pressure rose to 5.84 MPa, then dropped to 5.04 MPa, and then rose to 6.49 MPa (Fig. 29), at which point the axial strains also increased sharply and then decayed rapidly (Figs. 30-31), and the circumferential strains decreased noticeably and then rose again (Figs. 32-33). The breakdown pressure was reached and a subhorizontal

hydrofracture was detected at mid-height on the surface of the specimen. Its orientation was perpendicular to the core axis (Fig. 34). This does not agree with the theory that the hydrofracture extends along a plane normal to the direction of σ_{1max} . The creation of the subhorizontal hydrofracture might be attributable to some local weakness of the rock in the horizontal plane perpendicular to the core axis. Martin (1990) reported the orientation of the microcracks found in rock cores obtained at the 240 level of the URL trends approximately 020° to 040°. This means microcracks present in Specimen 2 were perpendicular to the core axis and thus provided the plane of weakness for the creation of a subhorizontal hydrofracture.

SCALE EFFECT

The results obtained in this experiment can be used to determine if there is any effect of specimen size on the tensile strength of the Lac du Bonnet grey granite. Firstly, the uniaxial tensile strength of the rock mass, T_{mass} , was determined in the following manner as suggested by Hoek (1990):

$$T_{mass} = \frac{\sigma_c}{2}(m - \sqrt{m^2 + 4s}) \quad (4)$$

For this granite, using values of σ_c , m and s obtained from boreholes 209-021-SV1 and 209-025-SV2, T_{mass} was found to be 5.56 MPa. The values of T_{mass} , T_{lab} and the mean tensile strength of 45-mm cores from borehole URL-05 are plotted against the rock mass volume in log scale in Figure 35. The plot shows that the specimen size does have an effect on the tensile strength of the rock. The tensile strength decreases from 8.06 to 7.40 to 5.56 MPa as the rock mass volume increases from 3.6×10^{-5} (45-mm diameter core) to 0.28 (600-mm diameter core) to 10^6 m^3 (100-m block). The lowering of the tensile strength is likely due to the increased probability of critical flaws in the larger specimens.

CONCLUSIONS

The apparatus and procedure to conduct the laboratory hydrofracturing test on 600-mm core samples and the equation to compute the value of T_{lab} have been developed and discussed in this report. The apparatus and instruments performed well during the

tests, with the exception of the strain gauge rosettes inside the sealed boreholes, which did not provide any useful data due to short circuits probably caused by pressurized water seeping through the sealant on to the gauges. Hydrofractures were successfully created in the two specimens used in these tests. From the test results, the following conclusions can be made.

A subvertical hydrofracture was created in Specimen 1 from borehole 209-054-RST2. From the results, the large-scale laboratory hydrofracturing tensile strength, T_{lab} , of the Lac du Bonnet grey granite was determined to be 7.40 MPa.

A subhorizontal hydrofracture was created in Specimen 2 from borehole 210-020-RST1. Although the direction of the hydrofracture was not normal, but parallel to the direction of the maximum stress (σ_{tmax}), the result was not entirely unexpected because microcracks present in Specimen 2 were perpendicular to the core axis. These microcracks provided a plane of weakness for the formation of a subhorizontal fracture before any vertical fracture could be created. Whereas, microcracks in Specimen 1 were parallel to the core axis and a subvertical hydrofracture was resulted. It is therefore quite reasonable to suggest that the orientation of a hydrofracture could be influenced by the orientation of microcracks present not only in the specimen in a laboratory test, but also in the borehole walls in the field.

Results of these tests and others on the Lac du Bonnet grey granite indicate that there is, indeed, some scale effect on tensile strength which causes it to decrease with increasing specimen size.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the help of Dr. B.C. Haimson of University of Wisconsin-Madison and Dr. N.A. Chandler of AECL Research in supervising the experiment. Dr. R.P. Young, T. Chow and S.D. Falls of Queen's University conducted the microseismic monitoring during the tests and their help during the experiment is appreciated. Gratitude is expressed to J. Foltá of CANMET and Cary James, a co-op student from University of Waterloo, for the preparation of specimens and the drafting of some of the diagrams.

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Table 1. Locations, orientations and dimensions of specimens.

Specimen number	Borehole	Downhole lengths (m)	Trend (degree)	Plunge (degree)	Specimen length (m)	Specimen diameter (mm)
1	209-054-RST2	0.63 - 1.51	030.03	-02.06	0.88	600
2	210-020-RST1	0.24 - 1.39	300.88	-02.35	1.15	600

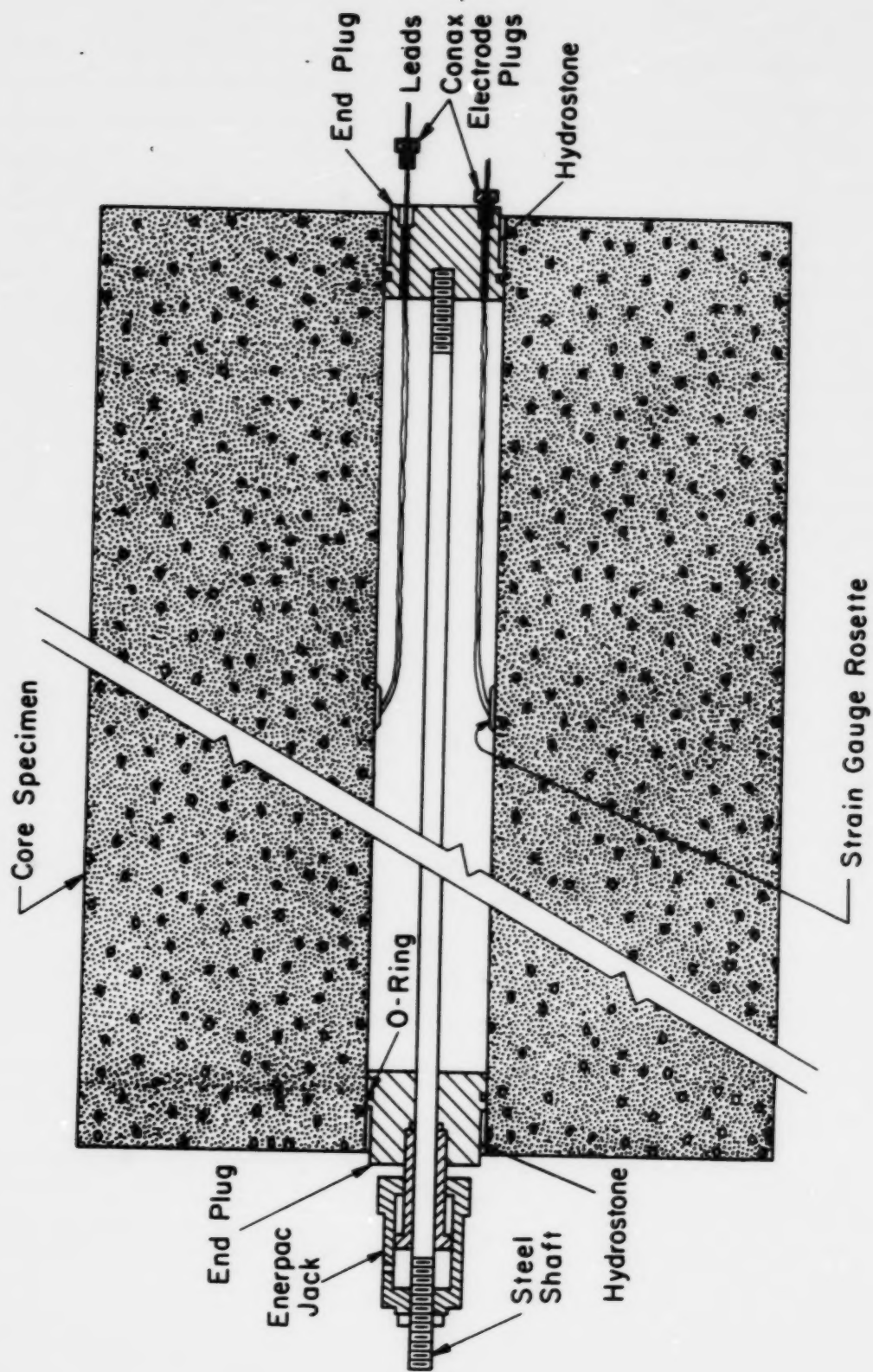


Figure 1. A schematic diagram of the sealed borehole in the cylindrical specimen.

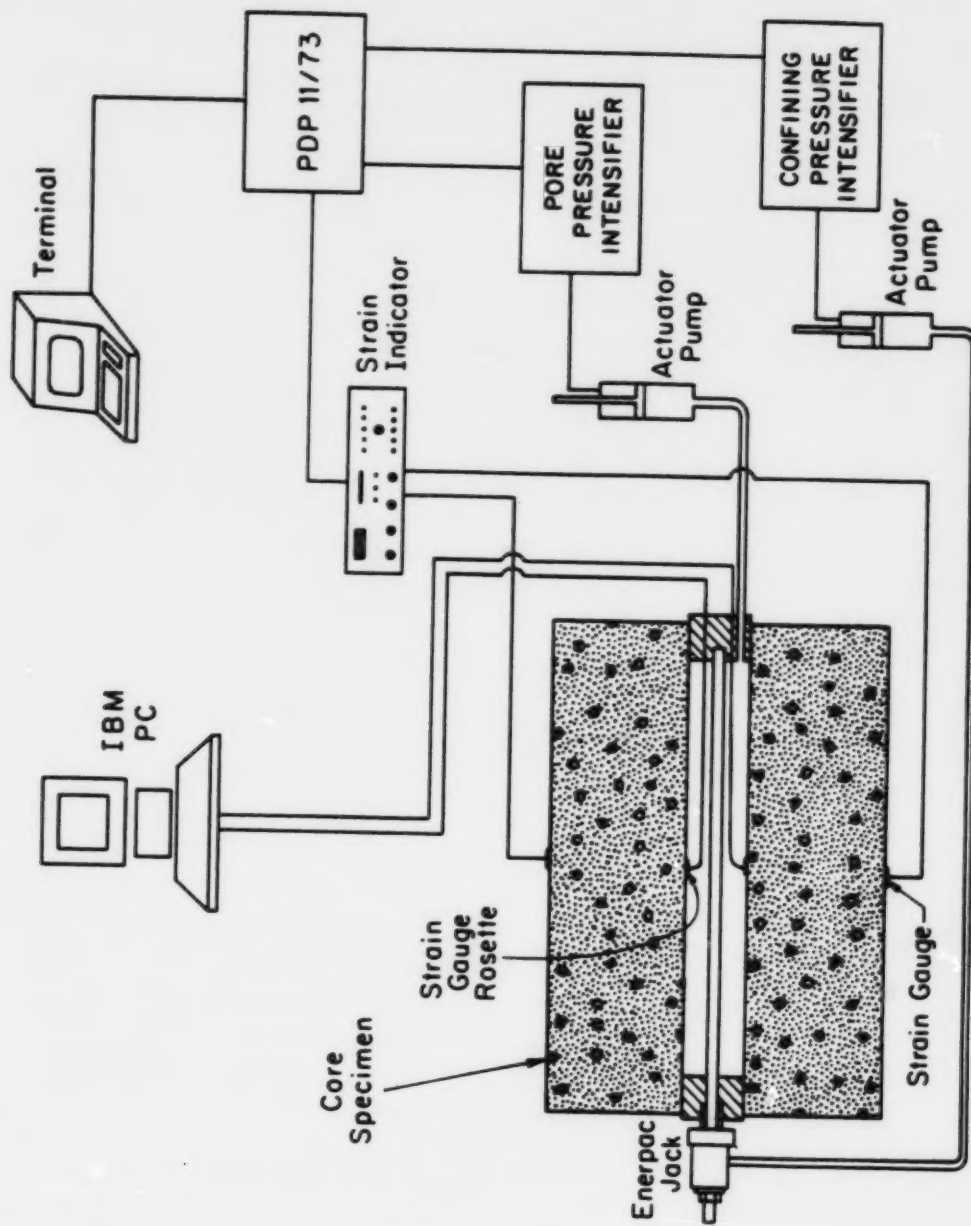


Figure 2. A schematic layout of the hydrofracturing test apparatus.

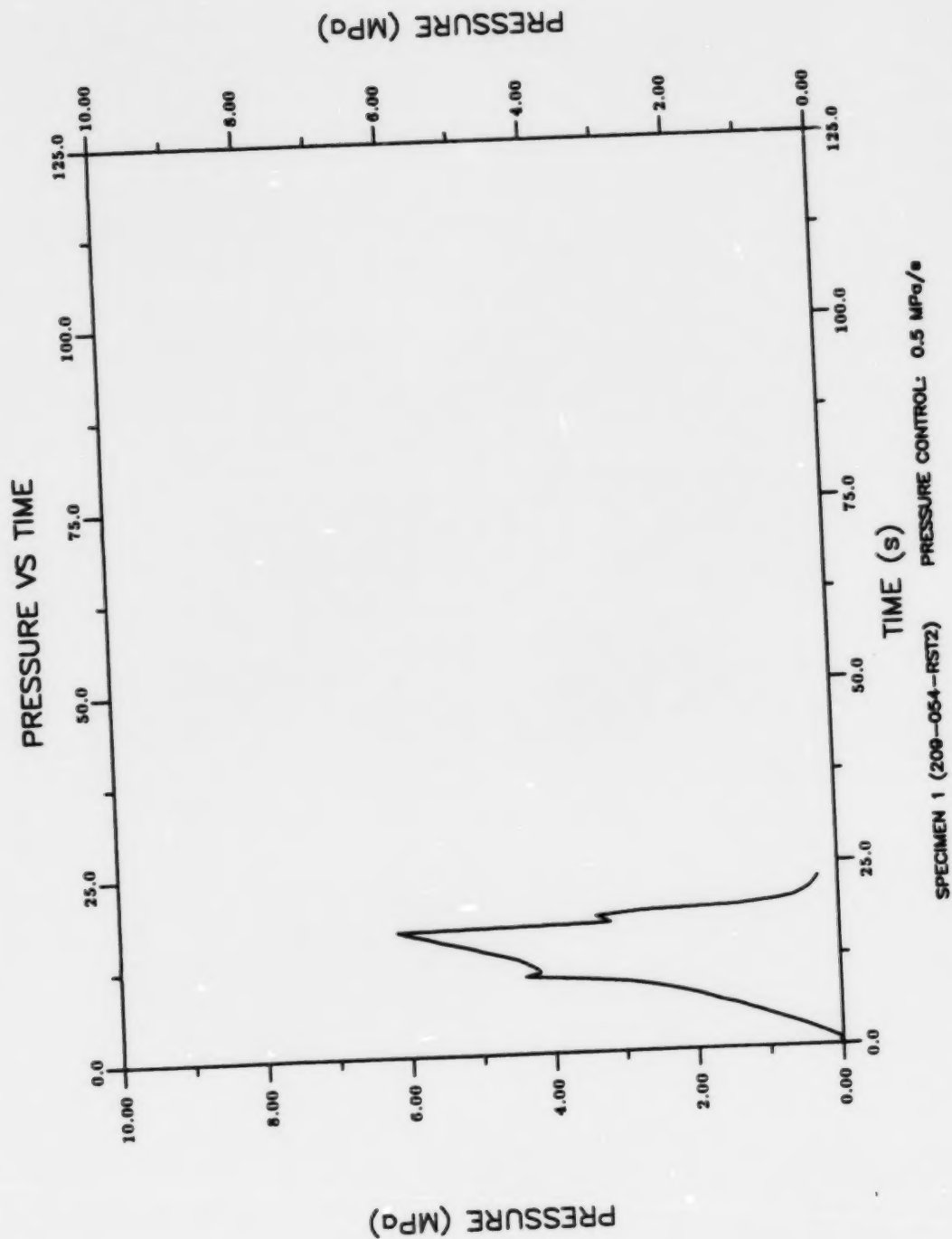


Figure 3. Pressure-time record for the test conducted on Specimen 1 at a pressure rate of 0.5 MPa/s.

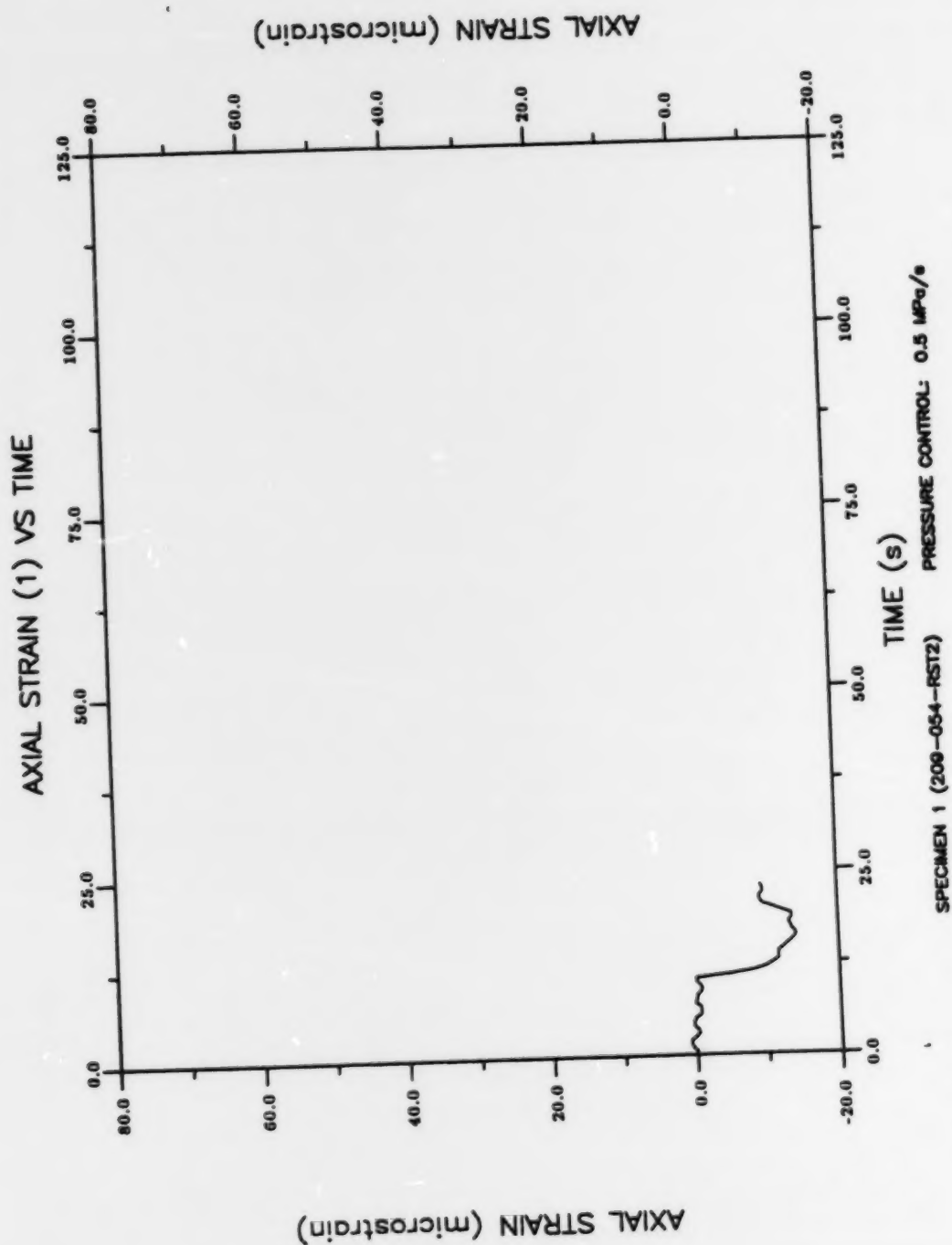


Figure 4. Strain-time record of axial strain No. 1 for the test conducted on Specimen 1 at a pressure rate of 0.5 MPa/s.

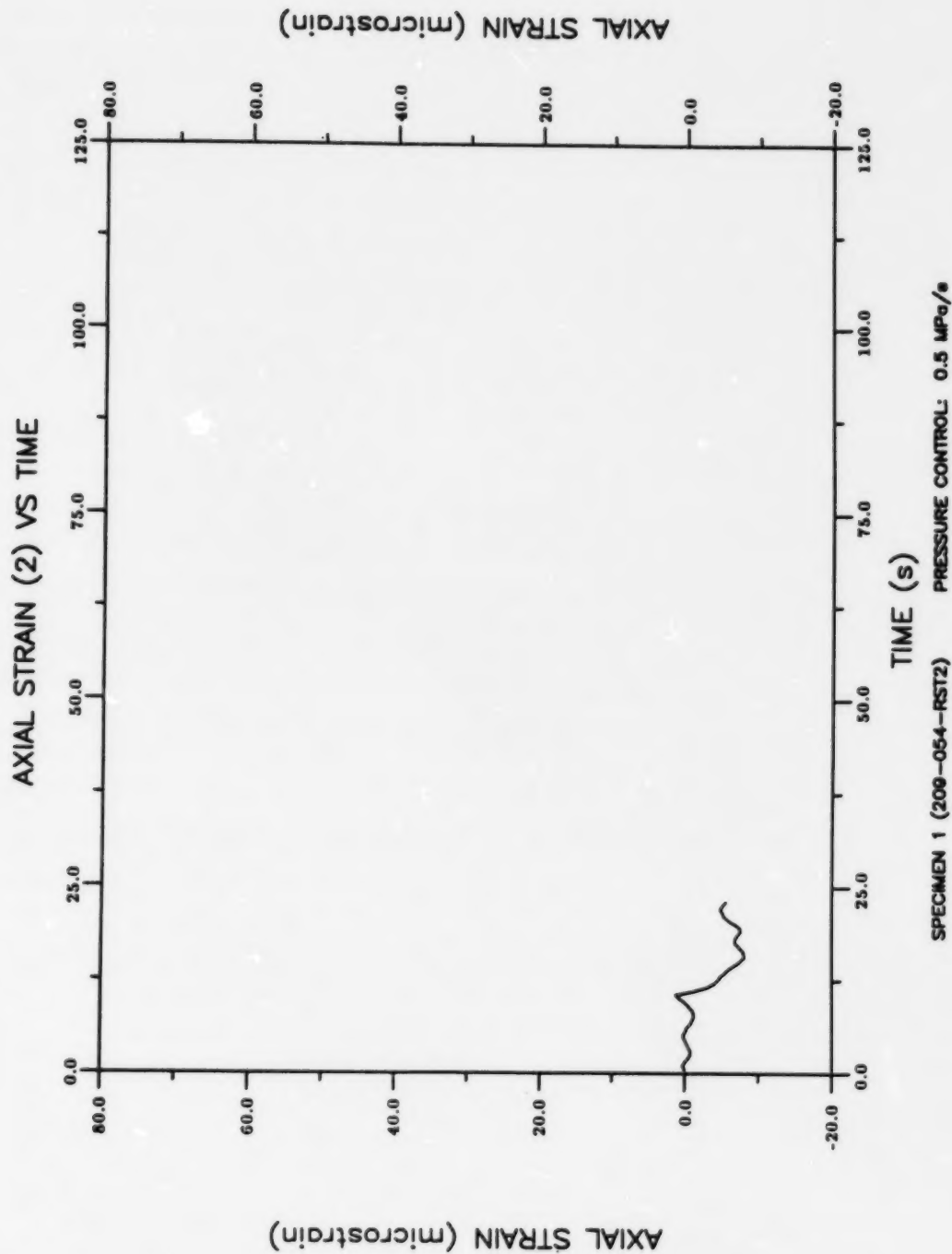


Figure 5. Strain-time record of axial strain No. 2 for the test conducted on Specimen 1 at a pressure rate of 0.5 MPa/s.

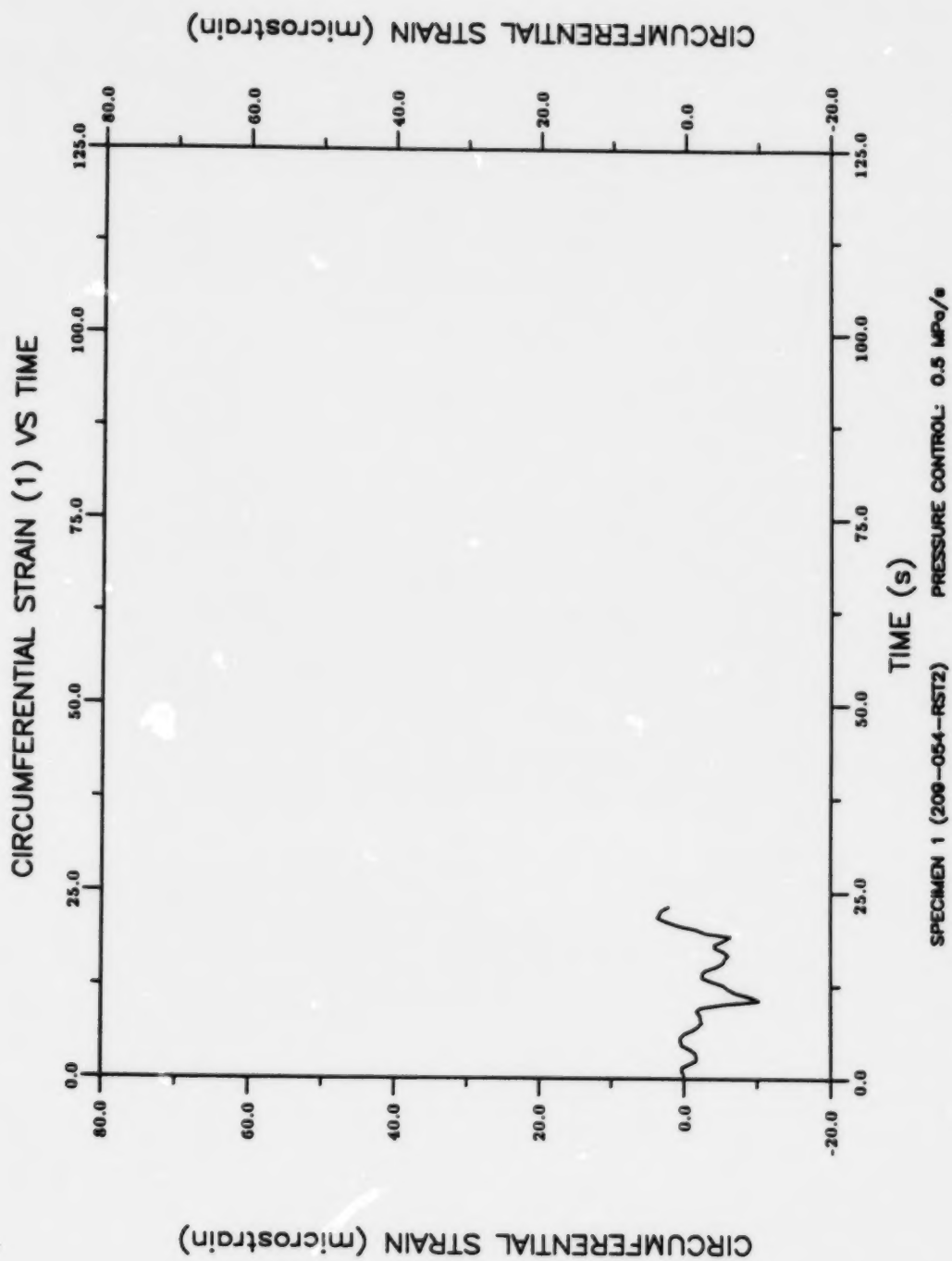


Figure 6. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 1 at a pressure rate of 0.5 MPa/s.

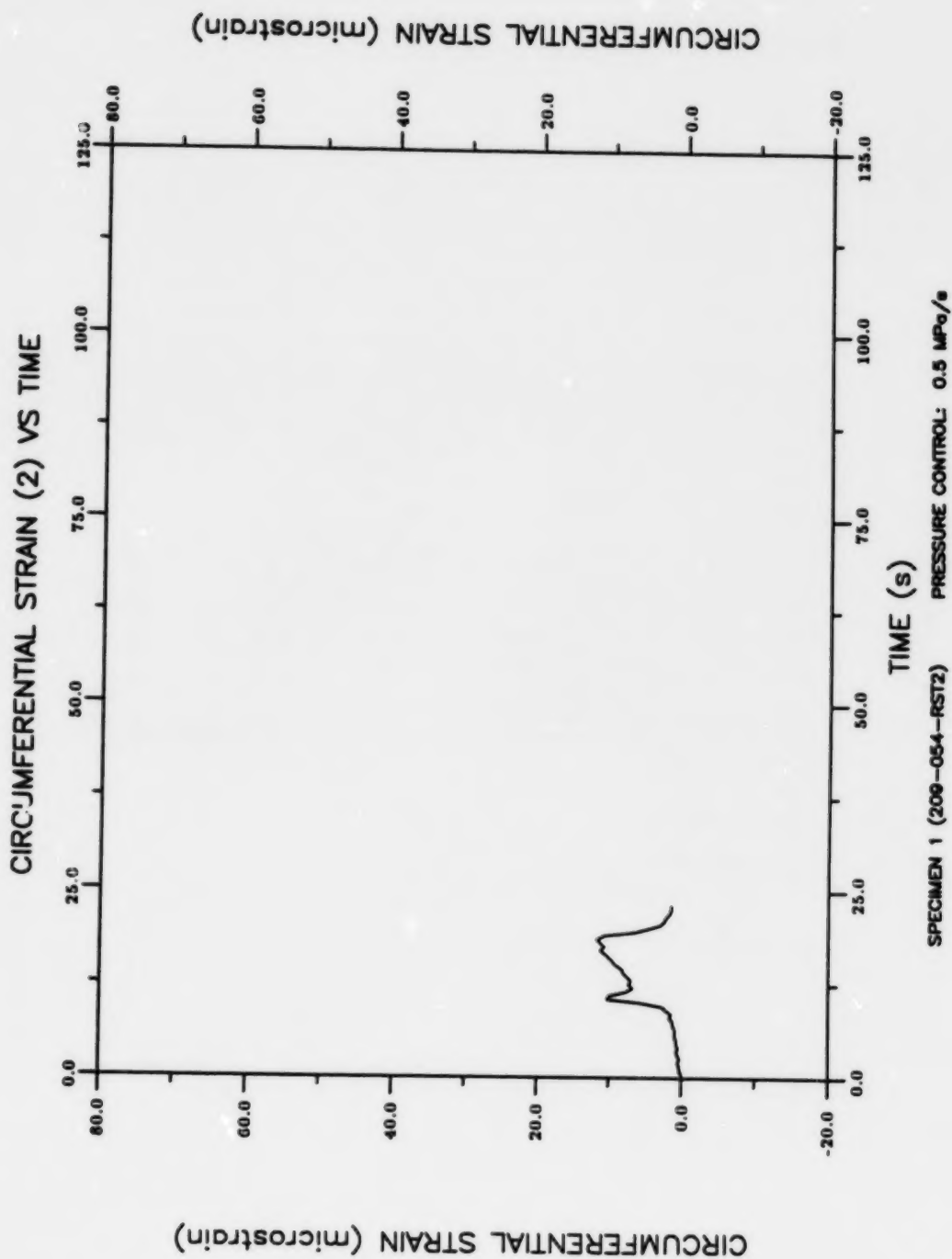


Figure 7. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 1 at a pressure rate of 0.5 MPa/s.

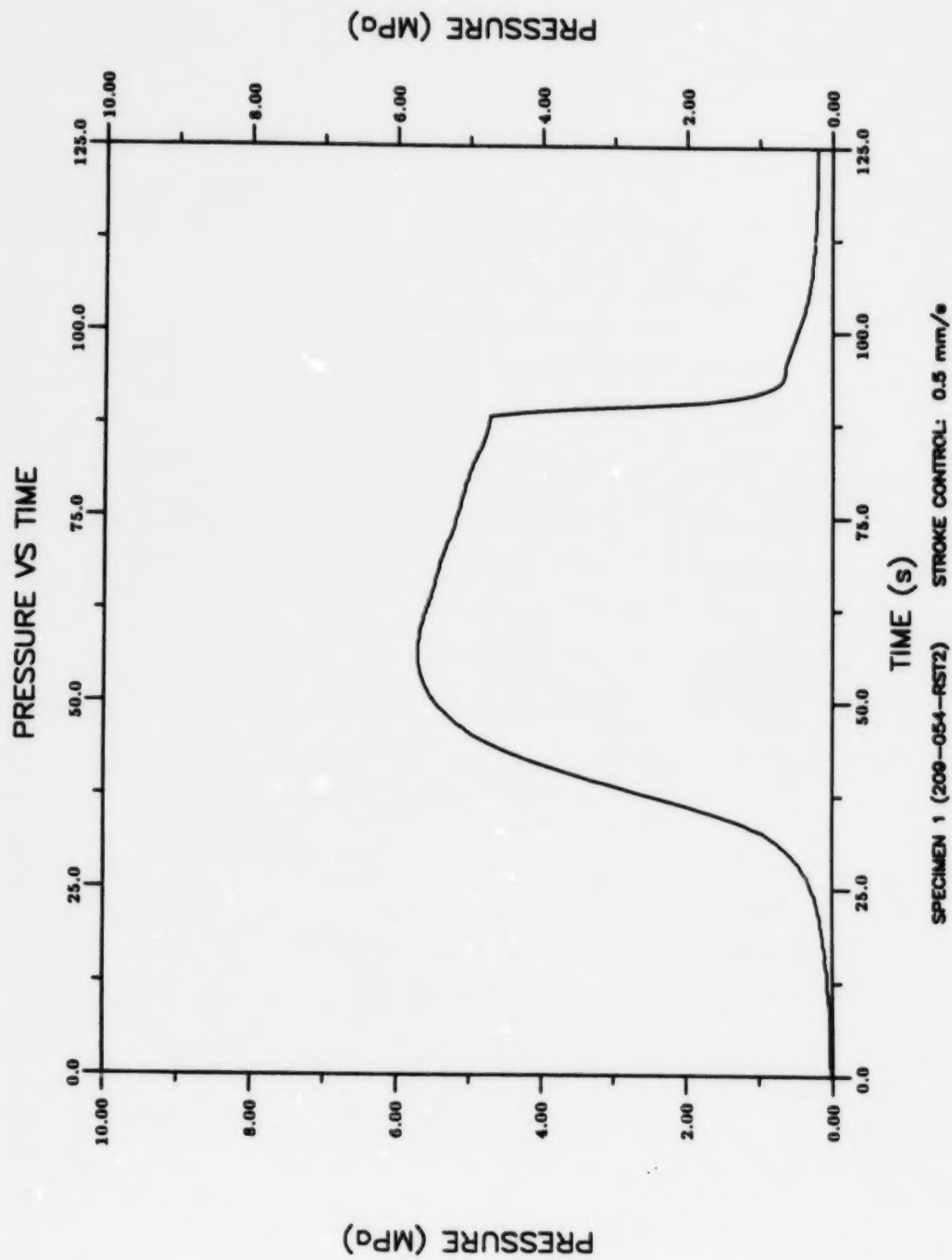


Figure 8. Pressure-time record for the test conducted on Specimen 1 at a stroke rate of 0.5 mm/s.

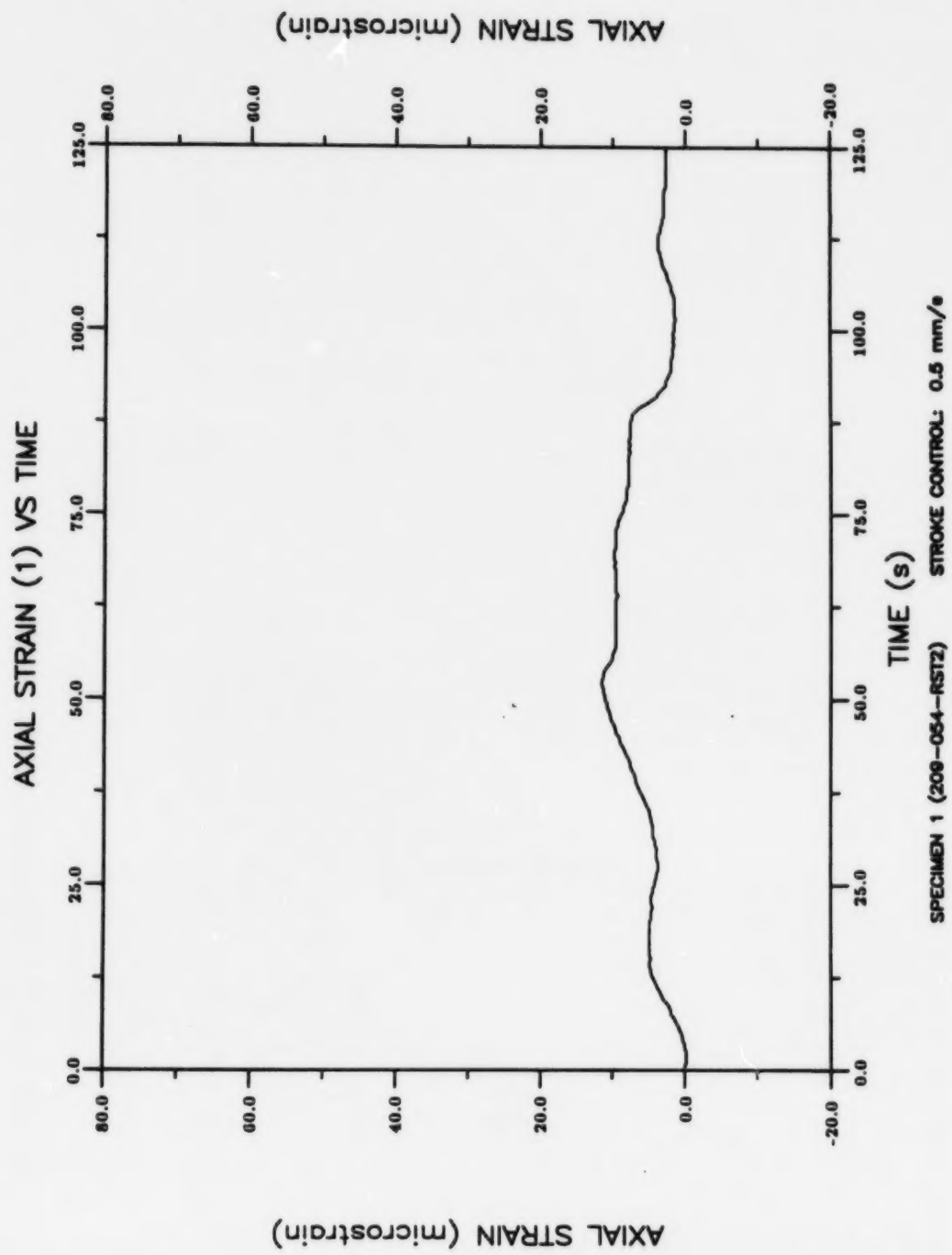


Figure 9. Strain-time record of axial strain No. 1 for the test conducted on Specimen 1 at a stroke rate of 0.5 mm/s.

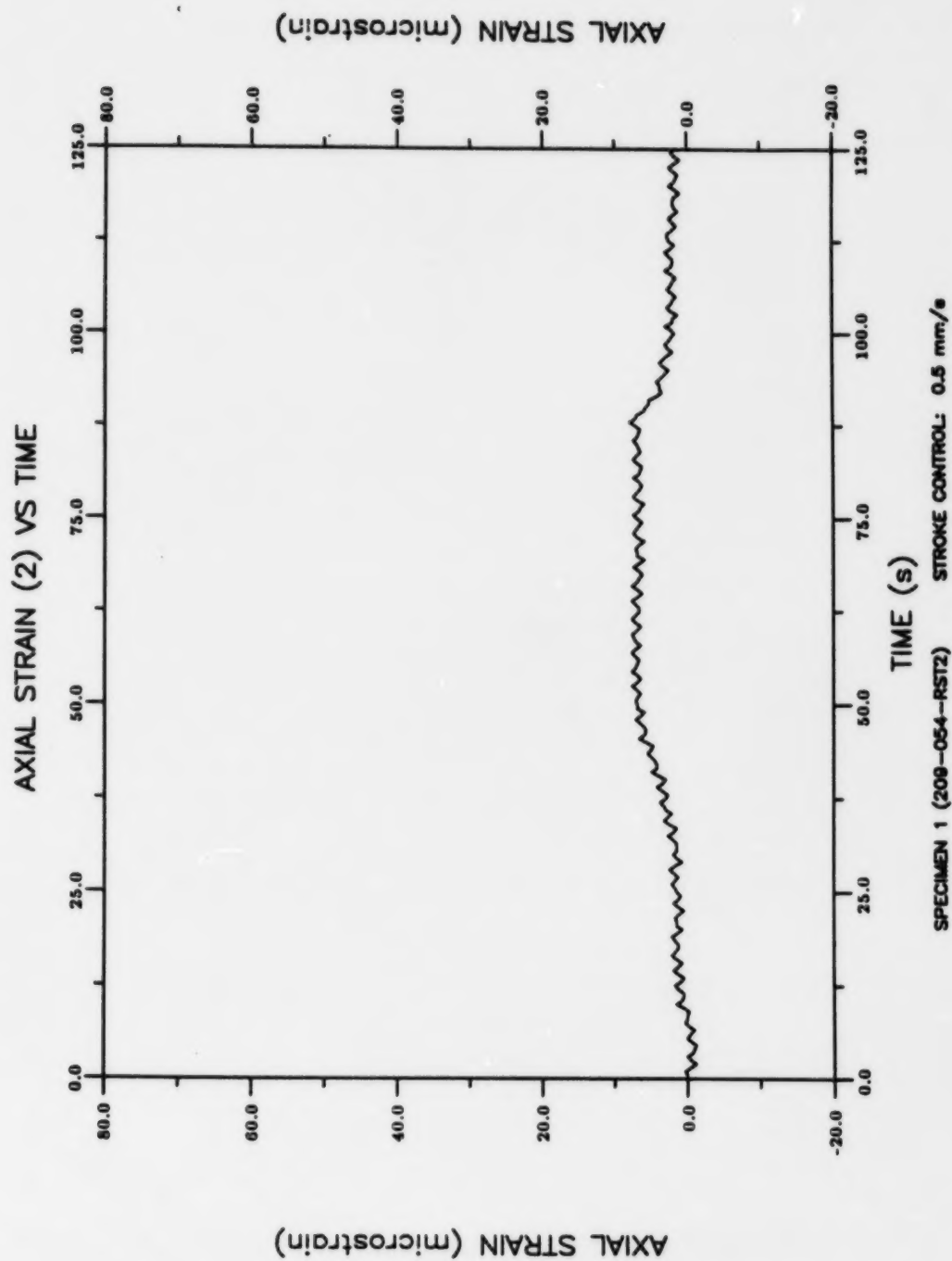


Figure 10. Strain-time record of axial strain No. 2 for the test conducted on Specimen 1 at a stroke rate of 0.5 mm/s.

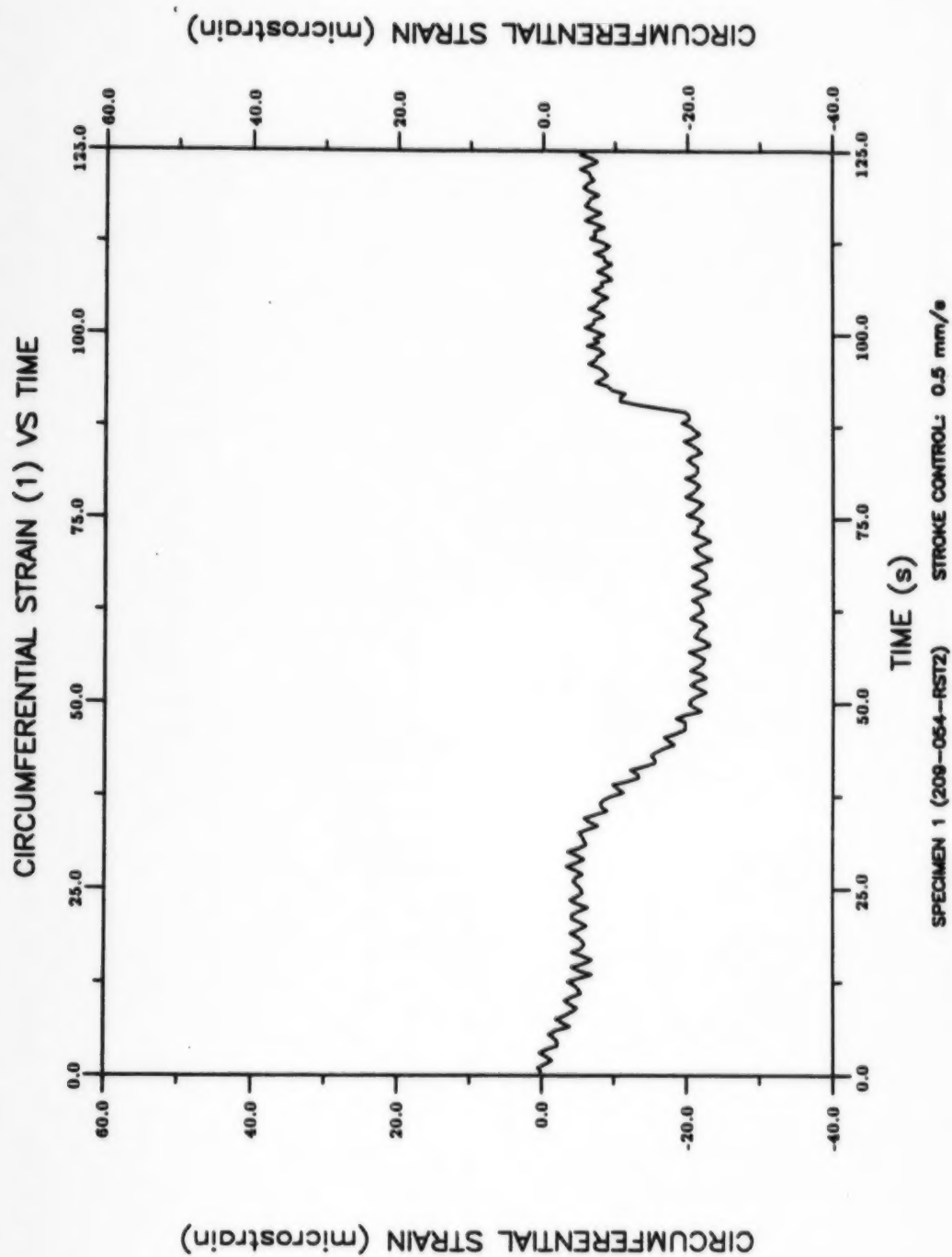


Figure 11. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 1 at a stroke rate of 0.5 mm/s.

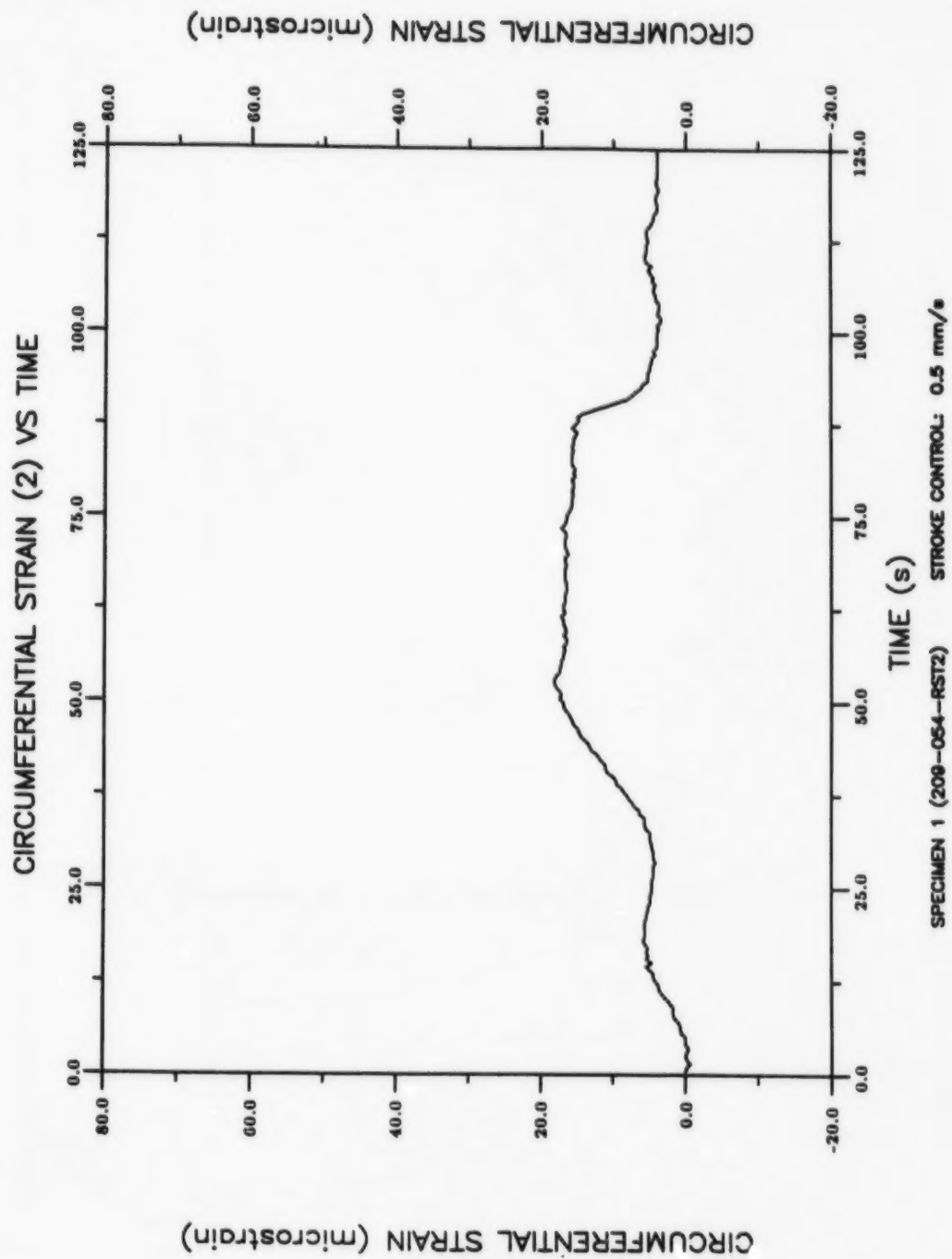


Figure 12. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 1 at a stroke rate of 0.5 mm/s.

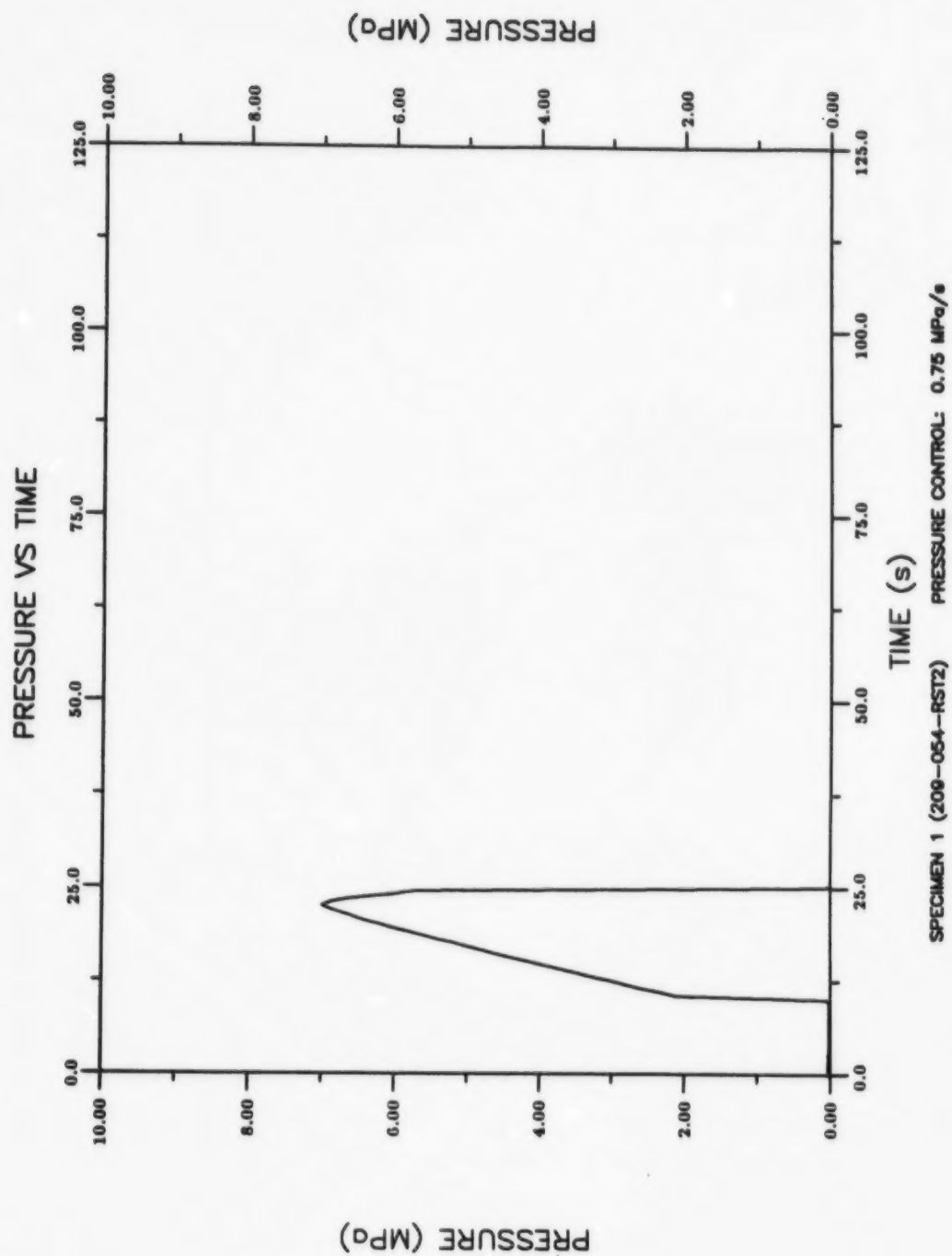


Figure 13. Pressure-time record for the test conducted on Specimen 1 at a pressure rate of 0.75 MPa/s.

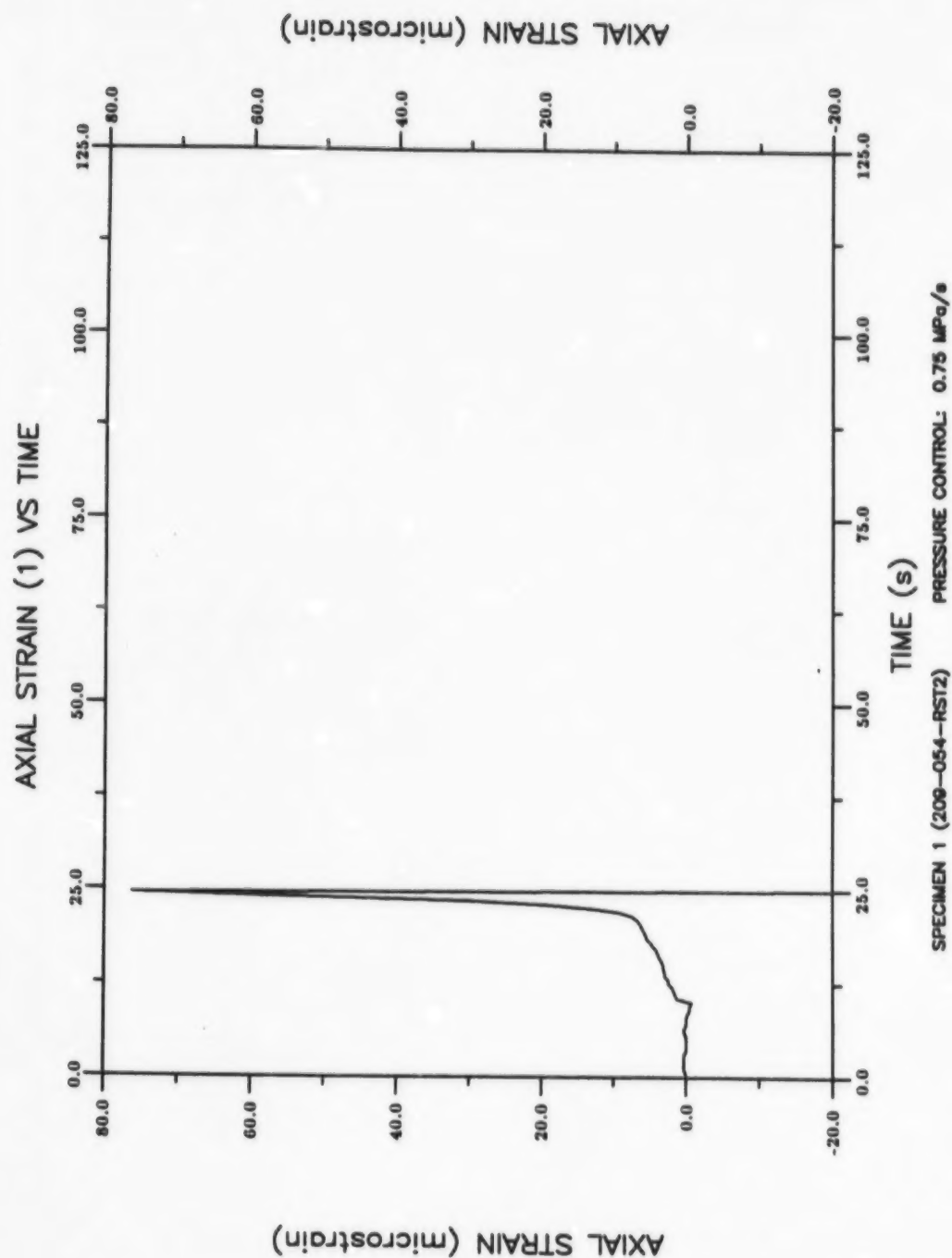


Figure 14. Strain-time record of axial strain No. 1 for the test conducted on Specimen 1 at a pressure rate of 0.75 MPa/s.

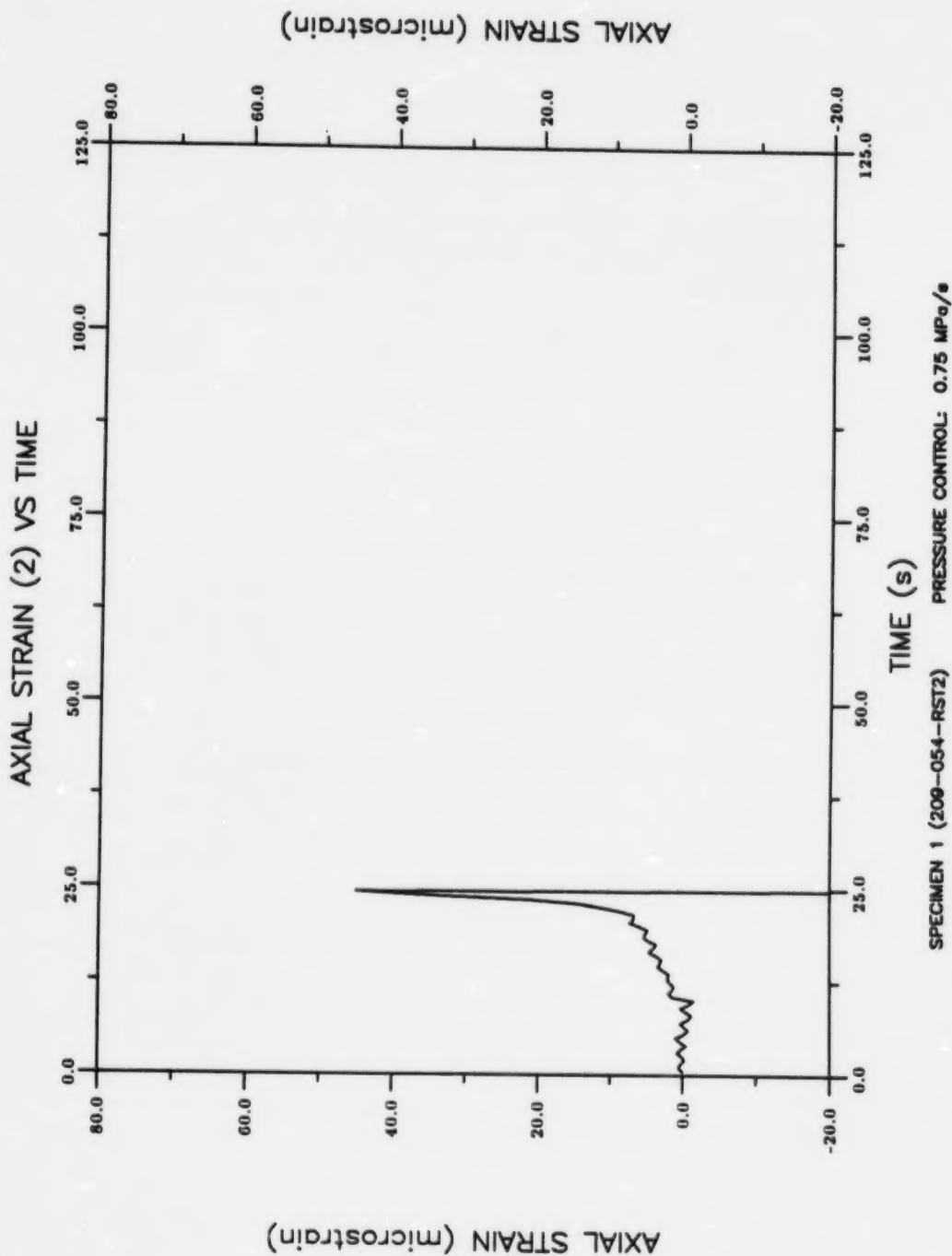


Figure 15. Strain-time record of axial strain No. 2 for the test conducted on Specimen 1 at a pressure rate of 0.75 MPa/s.

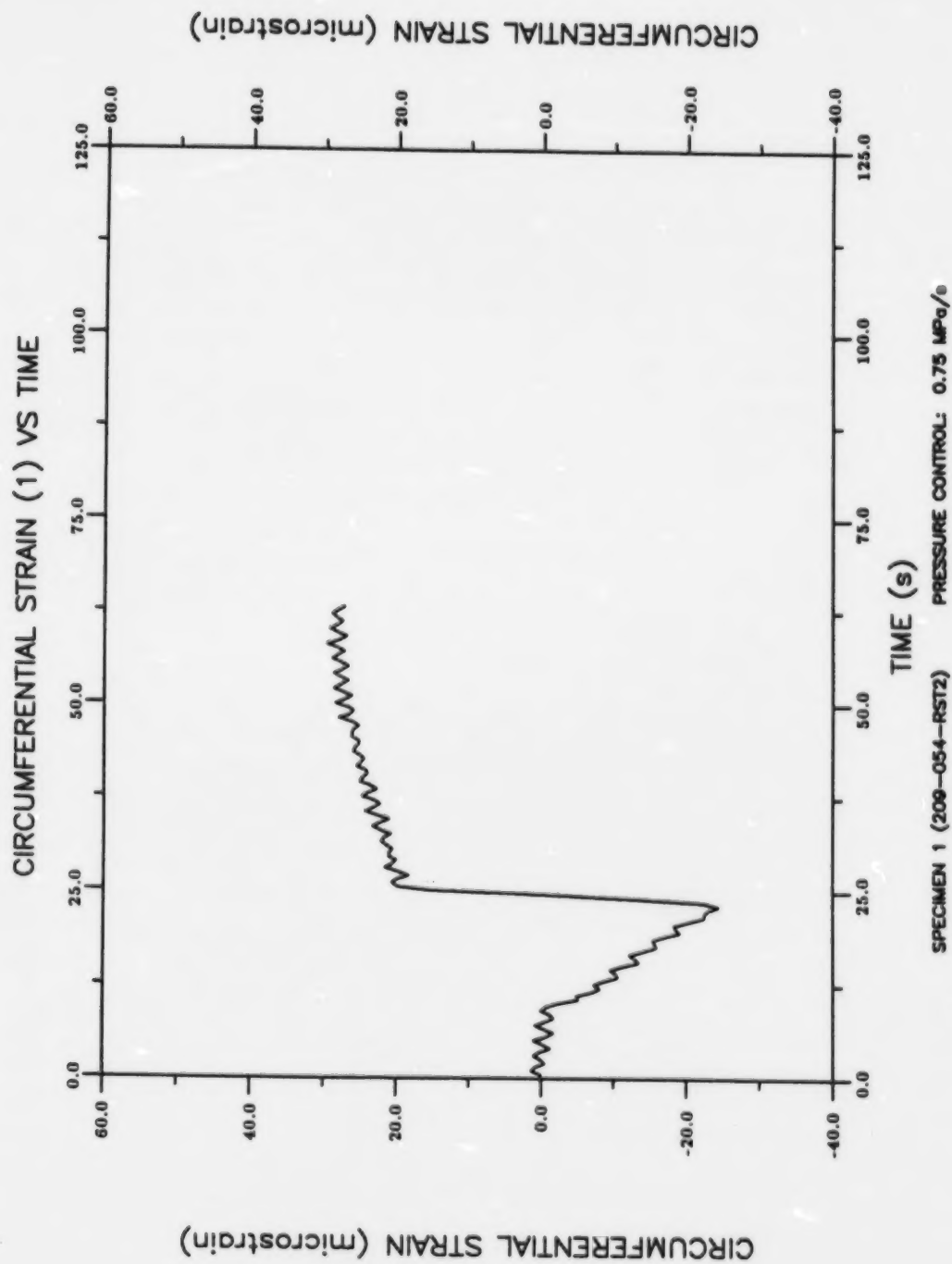


Figure 16. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 1 at a pressure rate of 0.75 MPa/s.

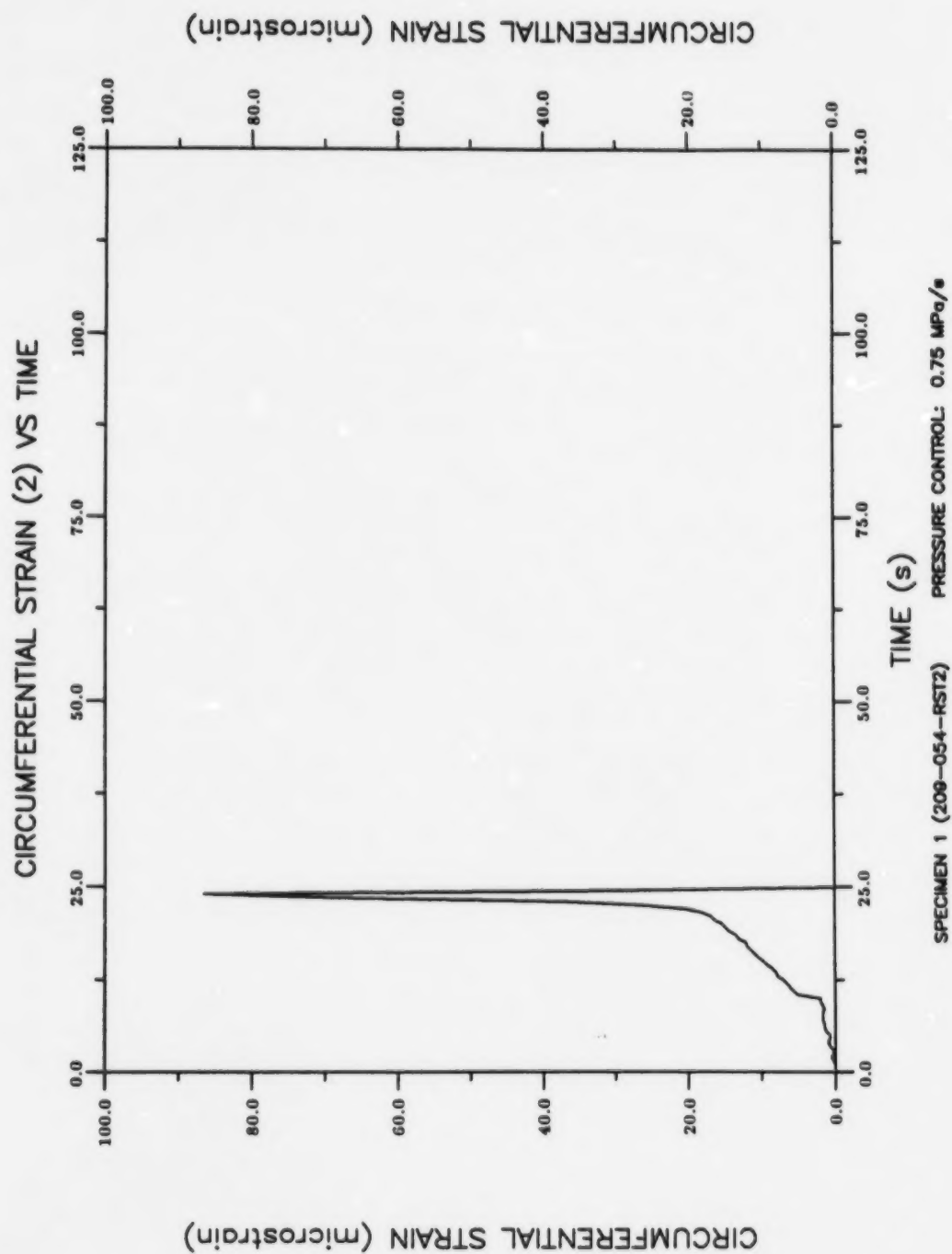


Figure 17. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 1 at a pressure rate of 0.75 MPa/s.

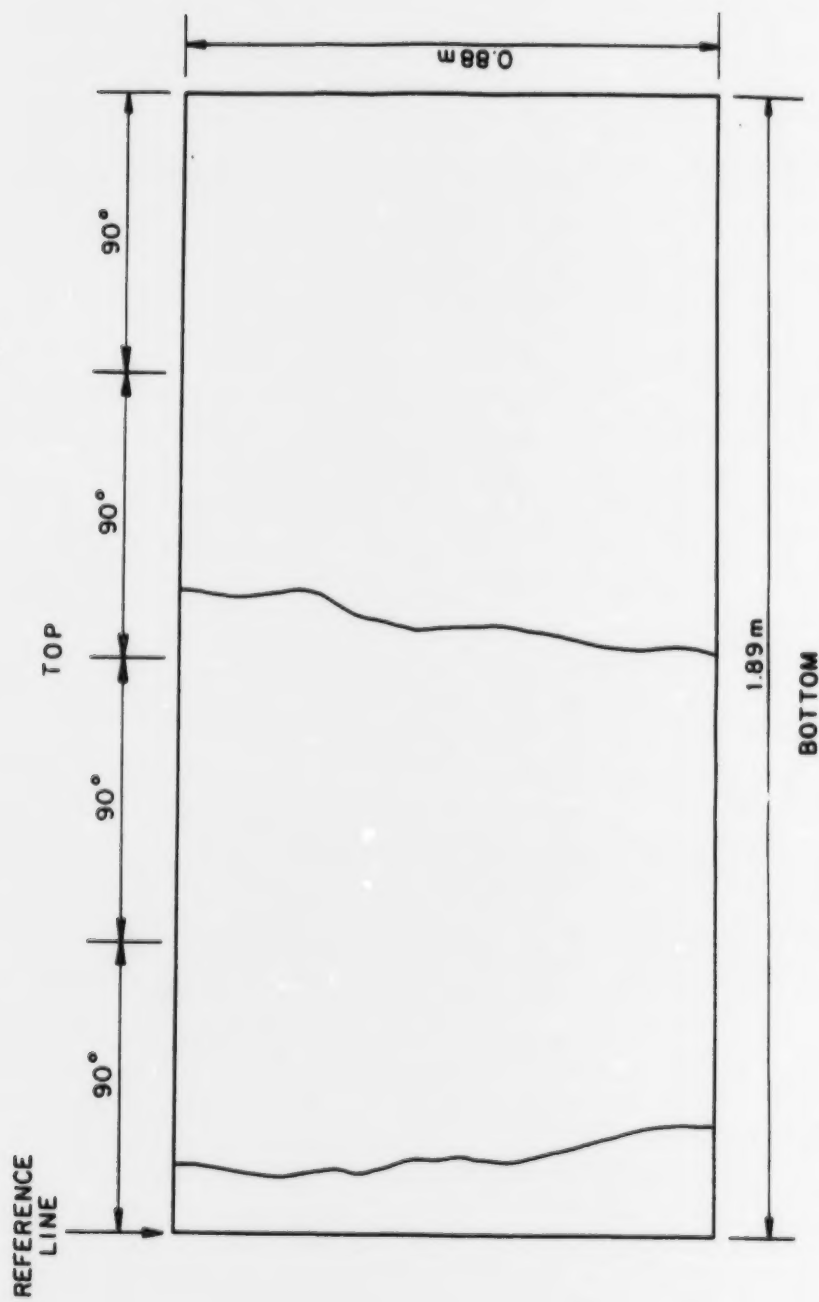


Figure 18. Trace of Hydrofracture on the surface of Specimen 1.

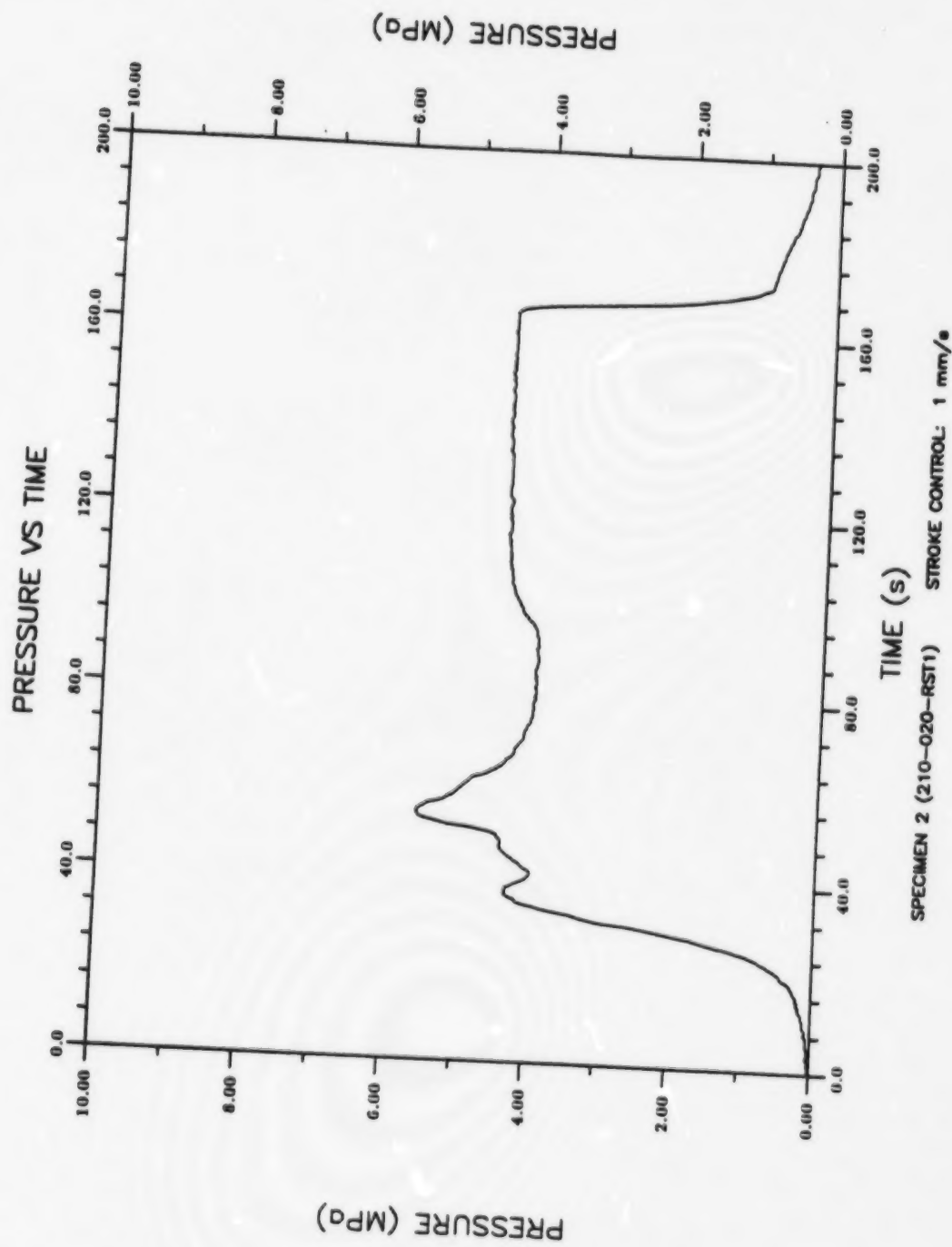


Figure 19. Pressure-time record for the test conducted on Specimen 2 at a stroke rate of 1 mm/s.

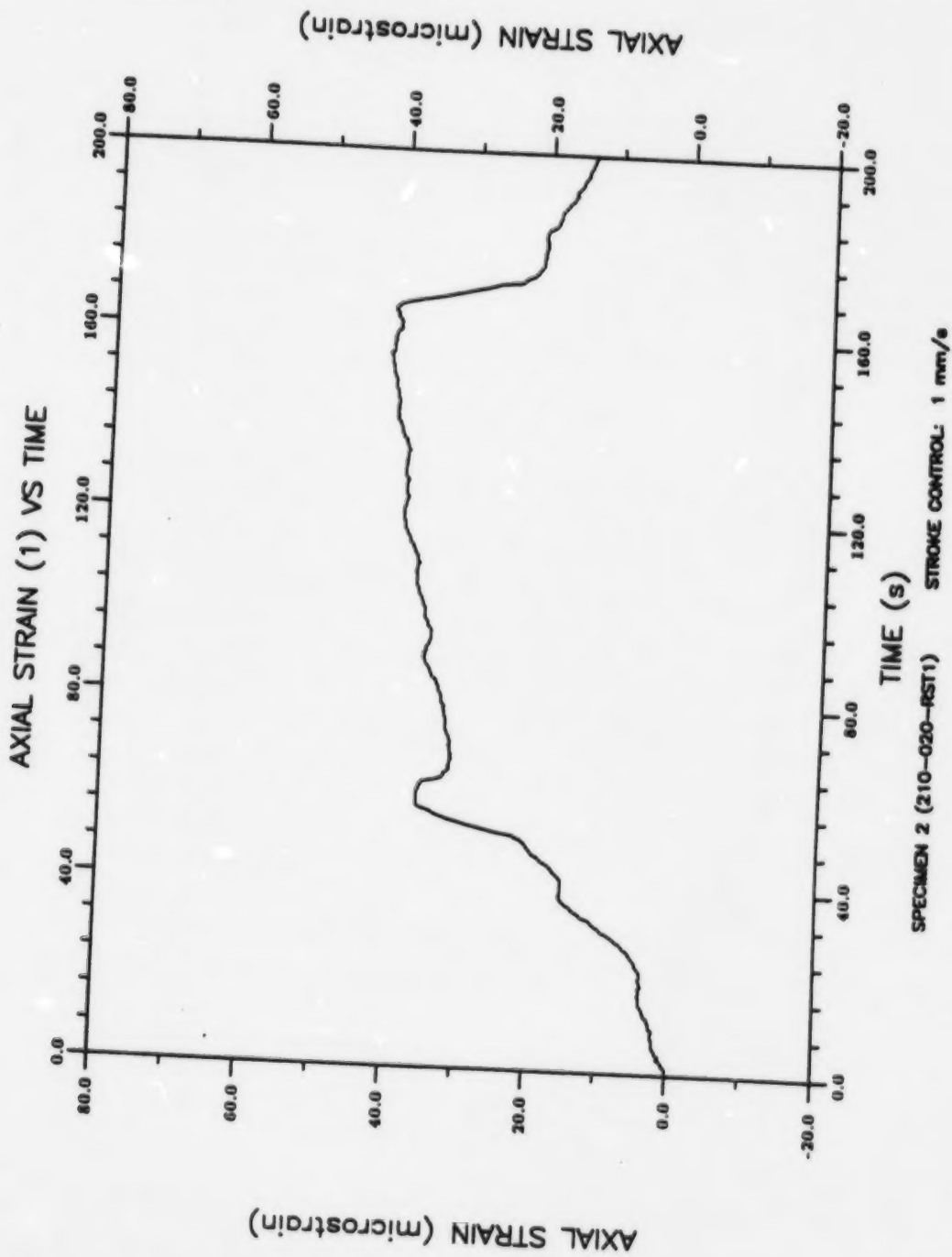


Figure 20. Strain-time record of axial strain No. 1 for the test conducted on Specimen 2 at a stroke rate of 1 mm/s.

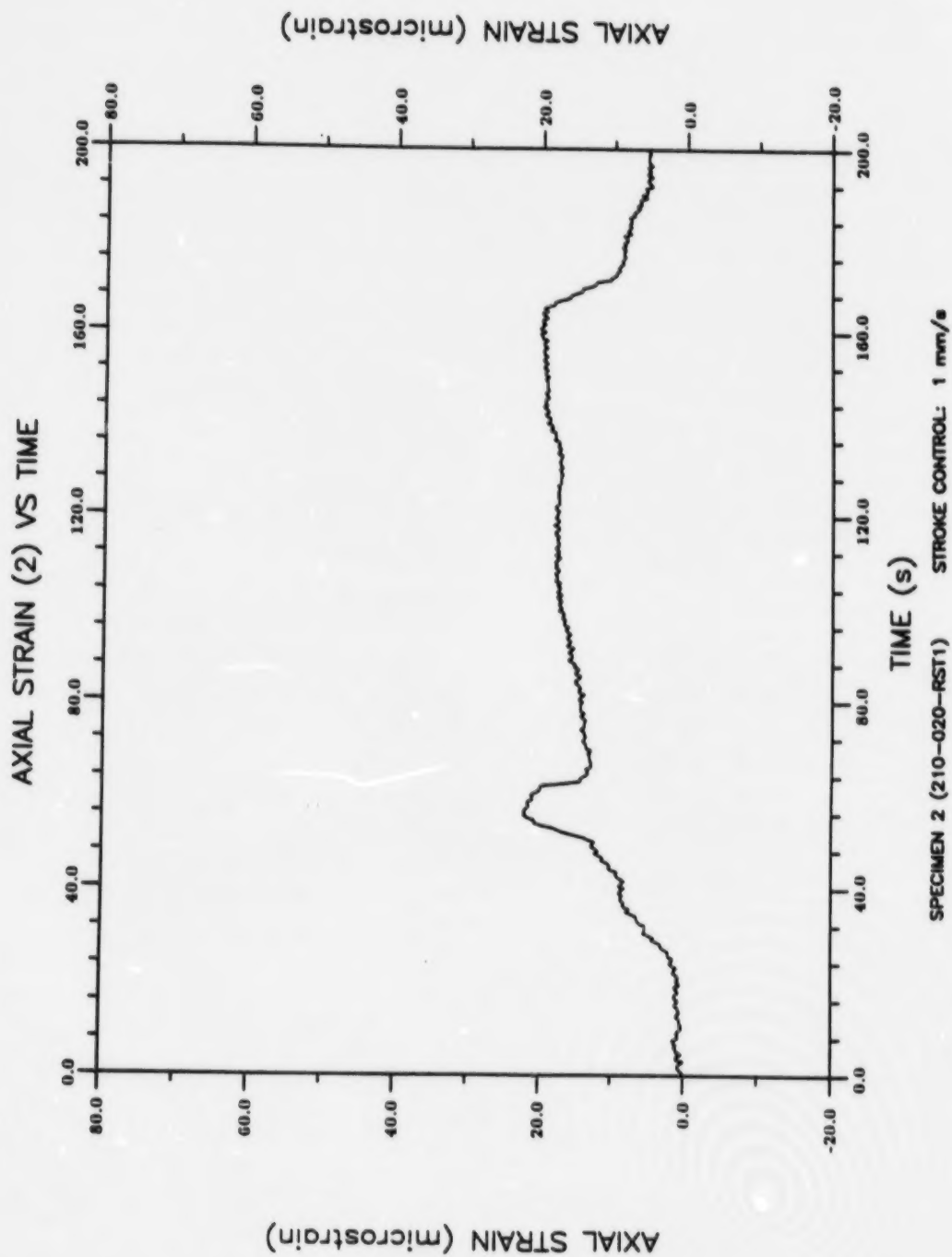


Figure 21. Strain-time record of axial strain No. 2 for the test conducted on Specimen 2 at a stroke rate of 1 mm/s.

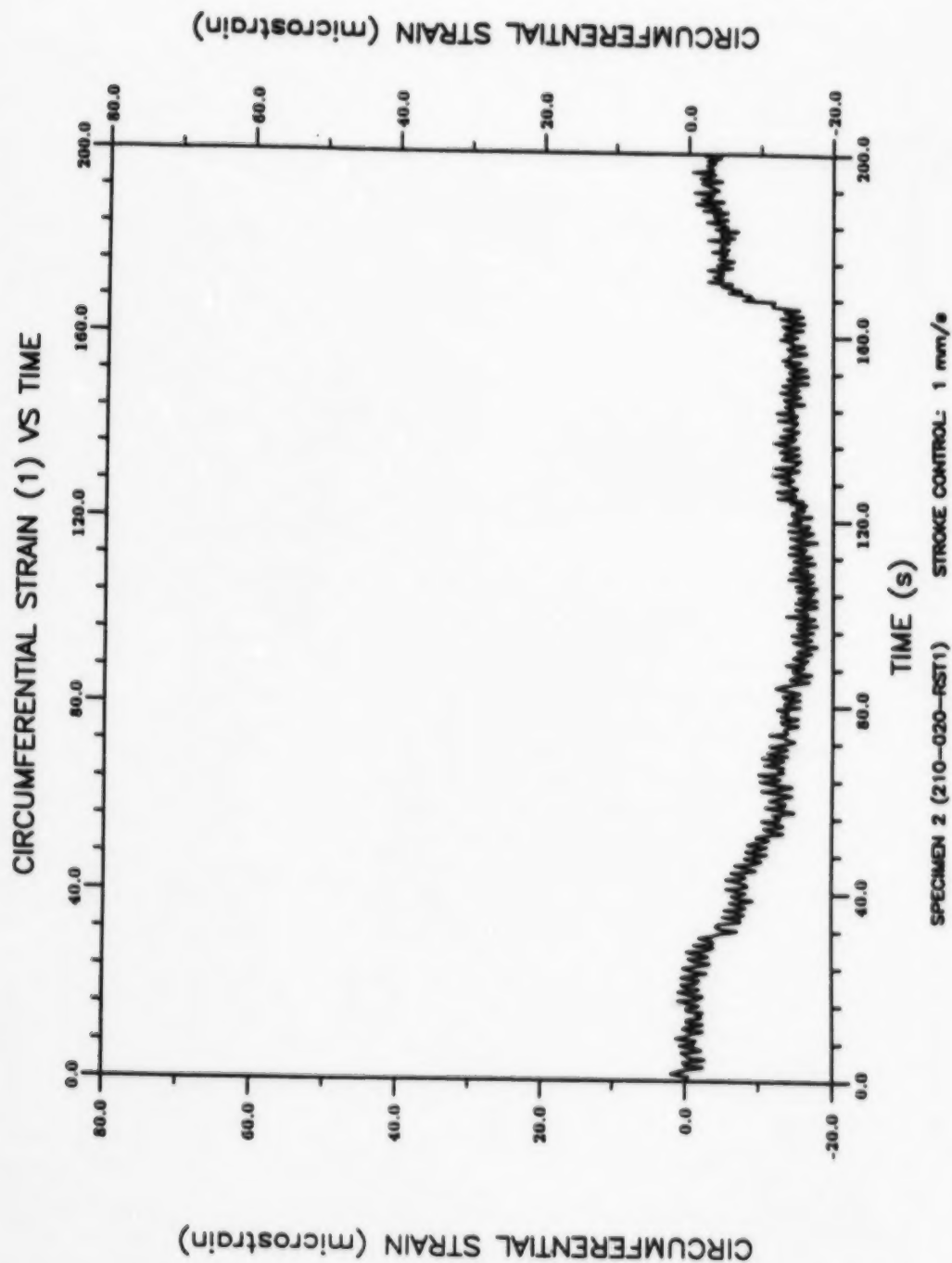


Figure 22. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 2 at a stroke rate of 1 mm/s.

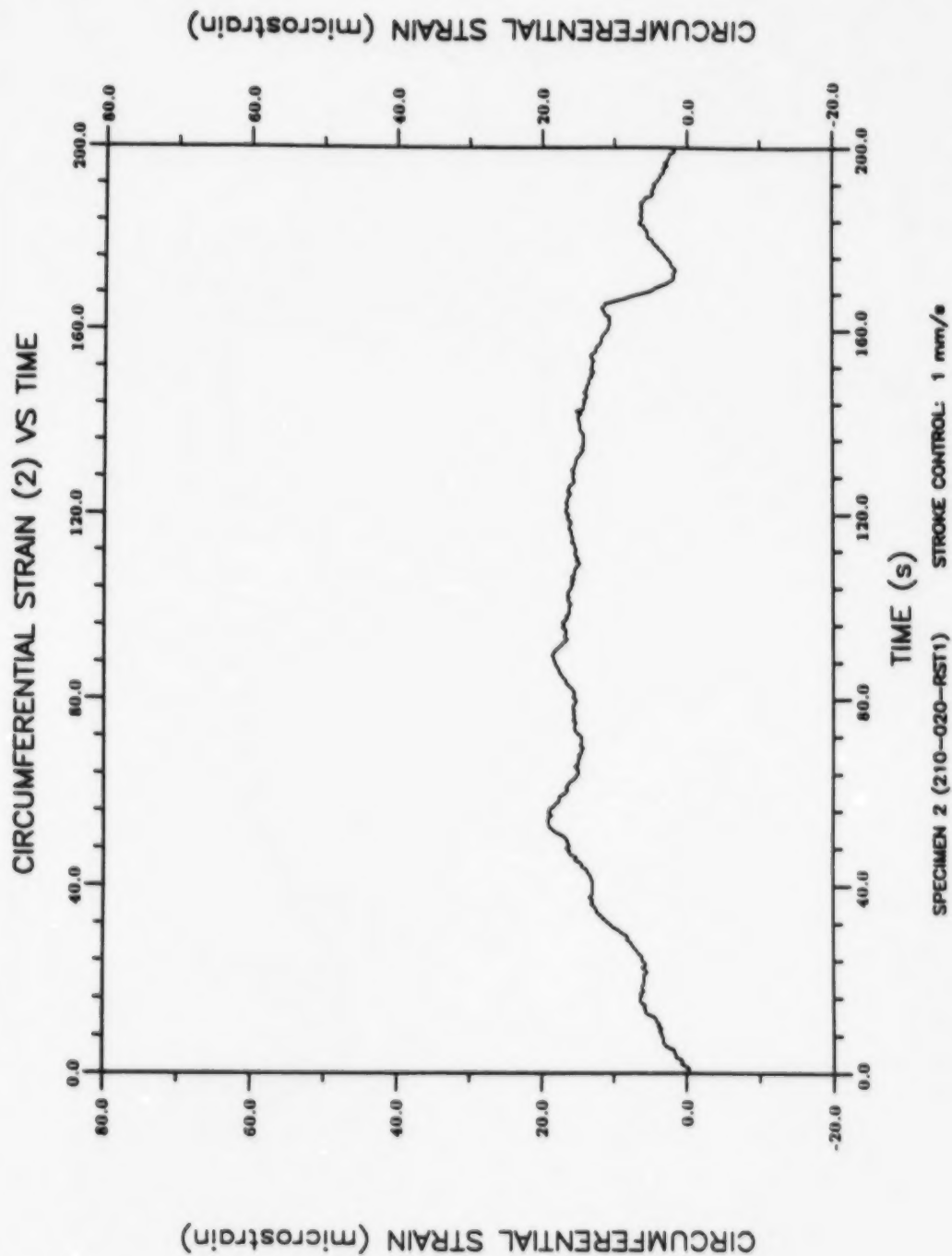


Figure 23. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 2 at a stroke rate of 1 mm/s.

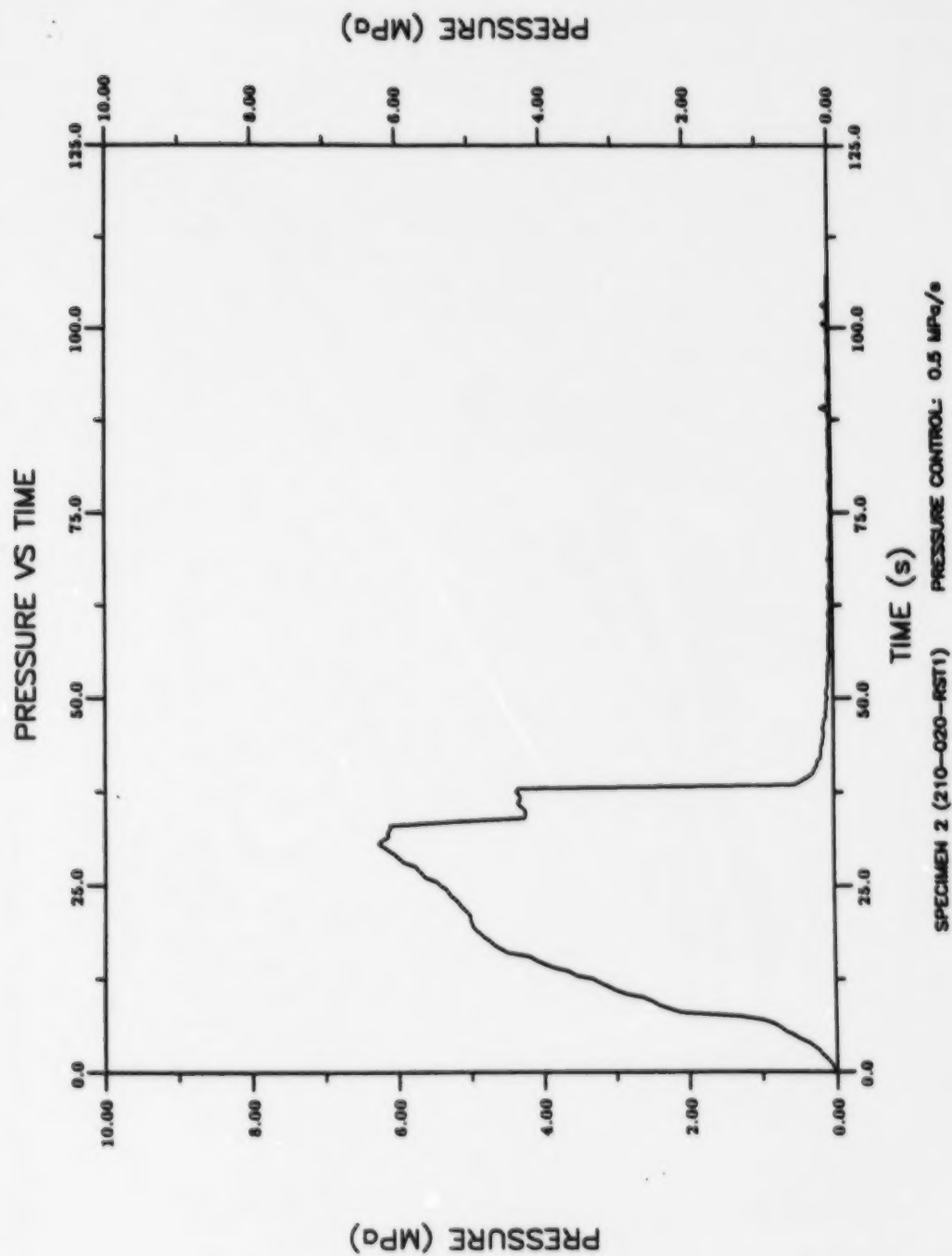


Figure 24. Pressure-time record for the test conducted on Specimen 2 at a pressure rate of 0.5 MPa/s.

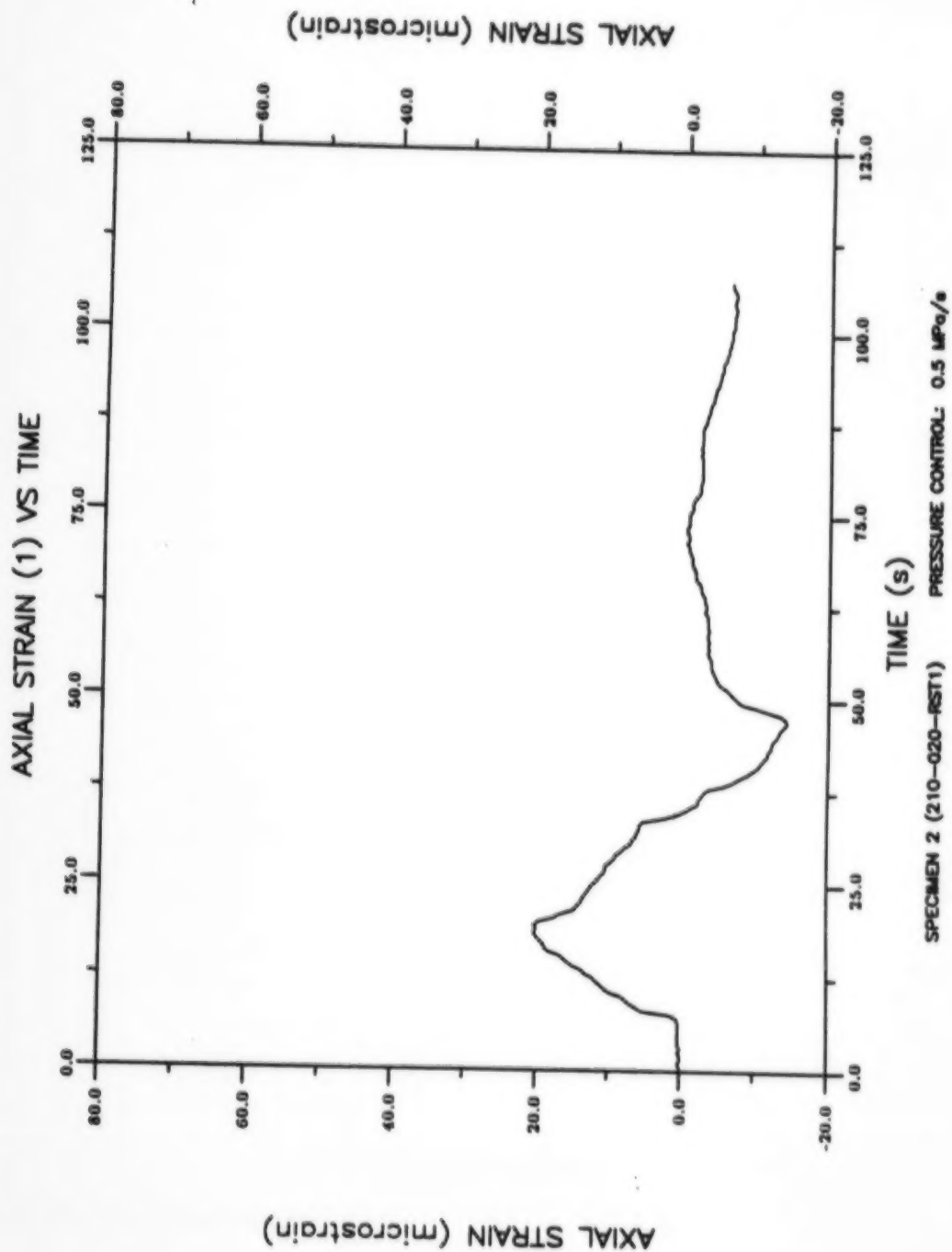


Figure 25. Strain-time record of axial strain No. 1 for the test conducted on Specimen 2 at a pressure rate of 0.5 MPa/s.

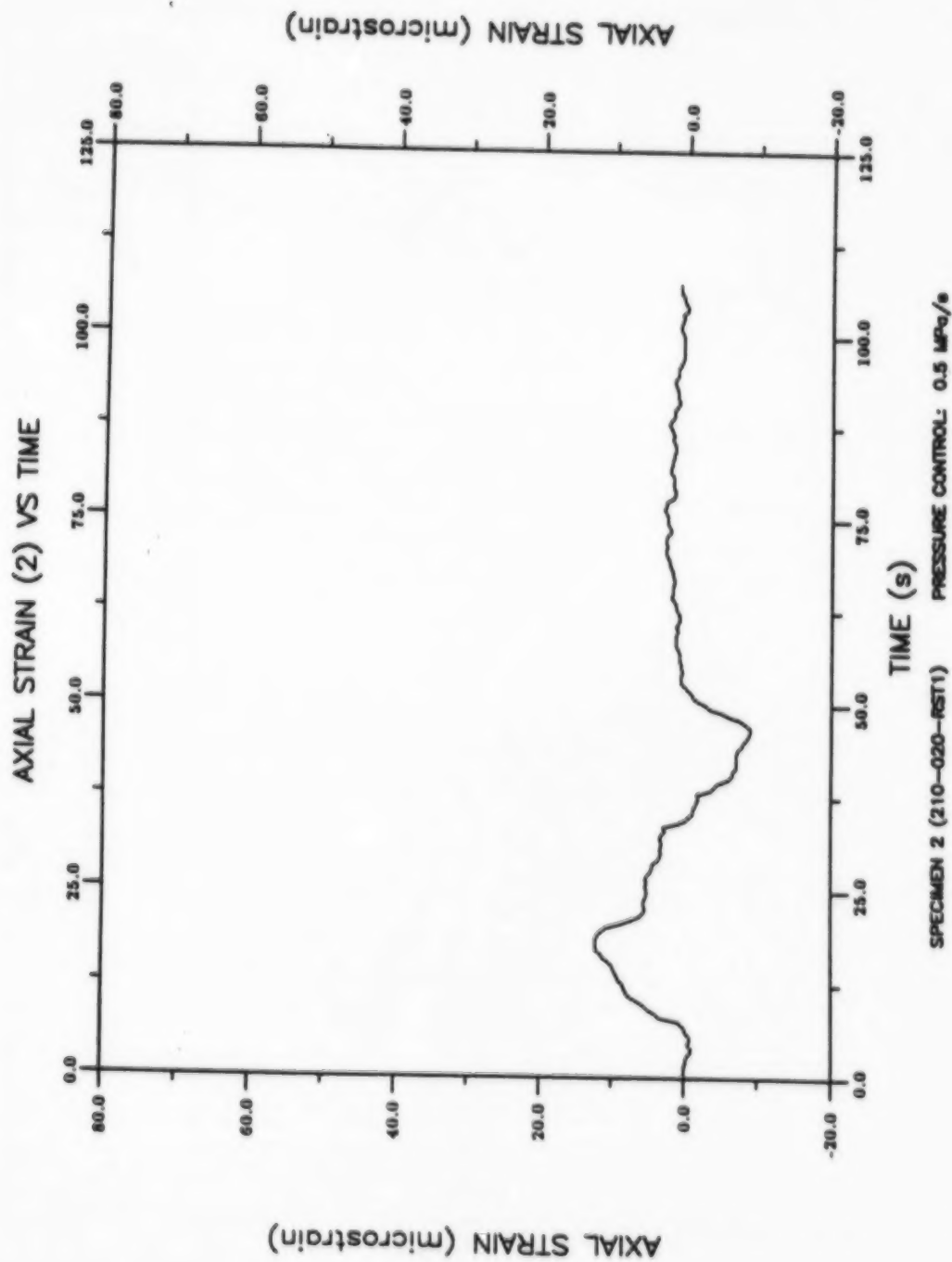


Figure 26. Strain-time record of axial strain No. 2 for the test conducted on Specimen 2 at a pressure rate of 0.5 MPa/s.

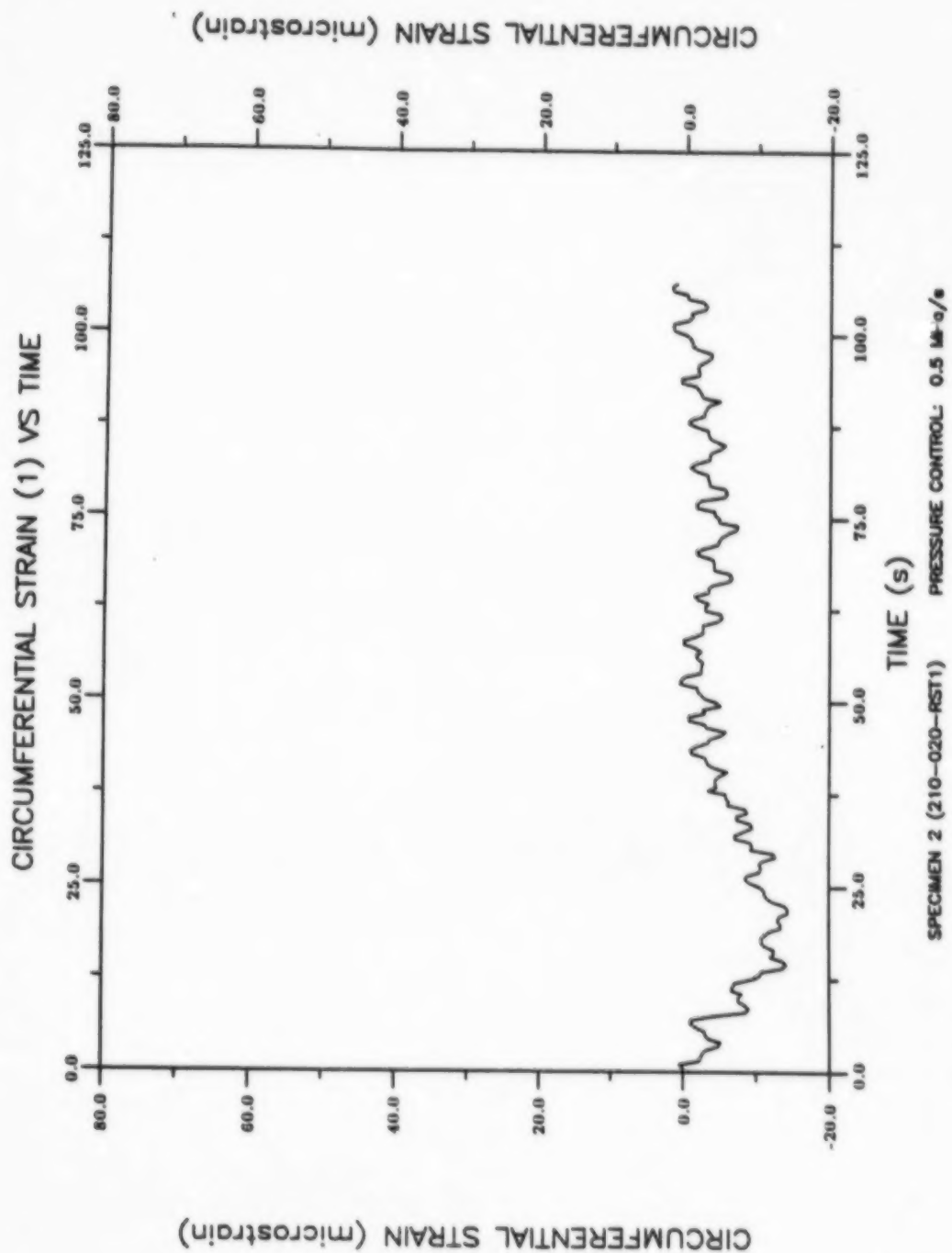


Figure 27. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 2 at a pressure rate of 0.5 MPa/s.

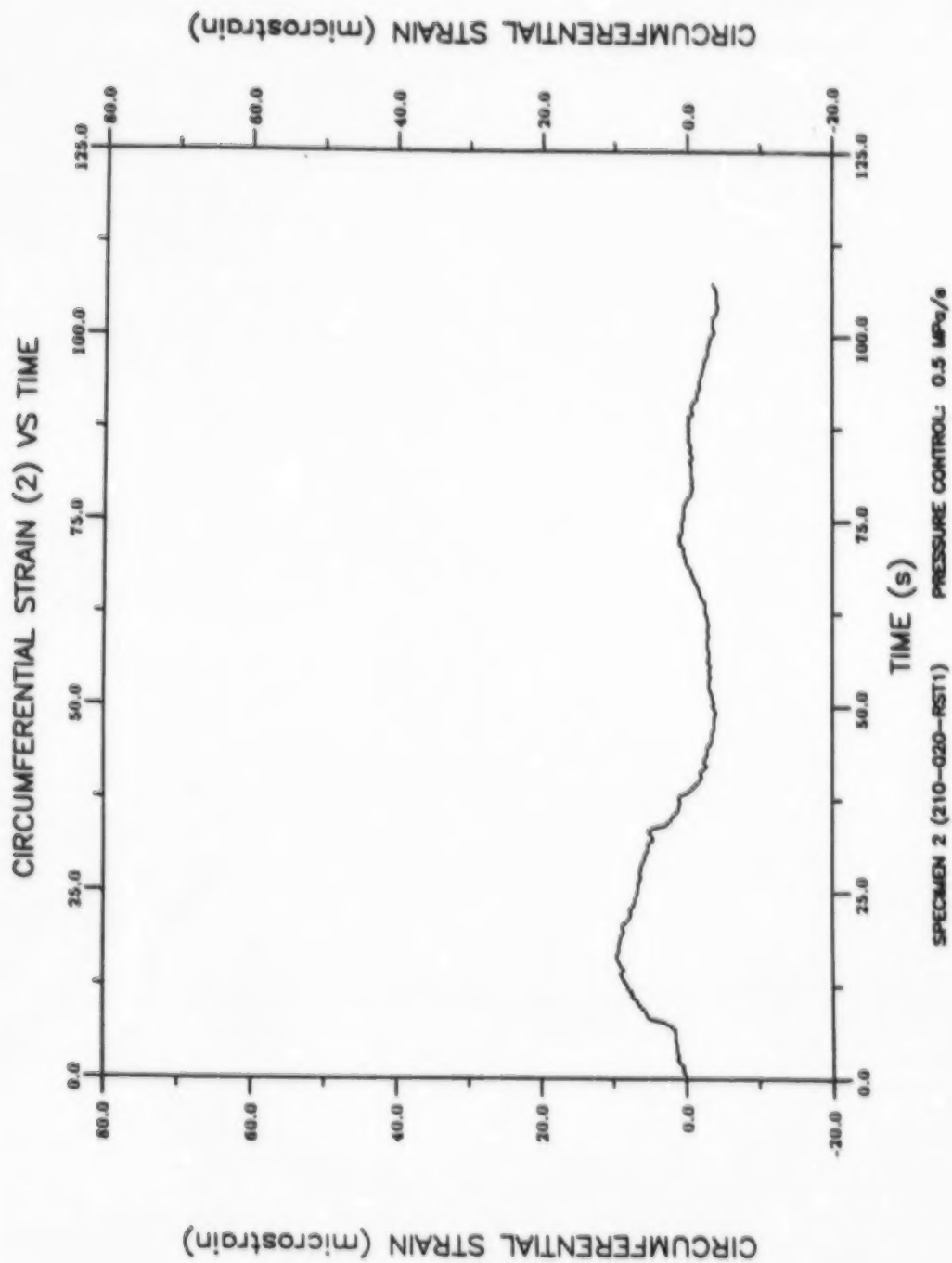


Figure 28. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 2 at a pressure rate of 0.5 MPa/s.

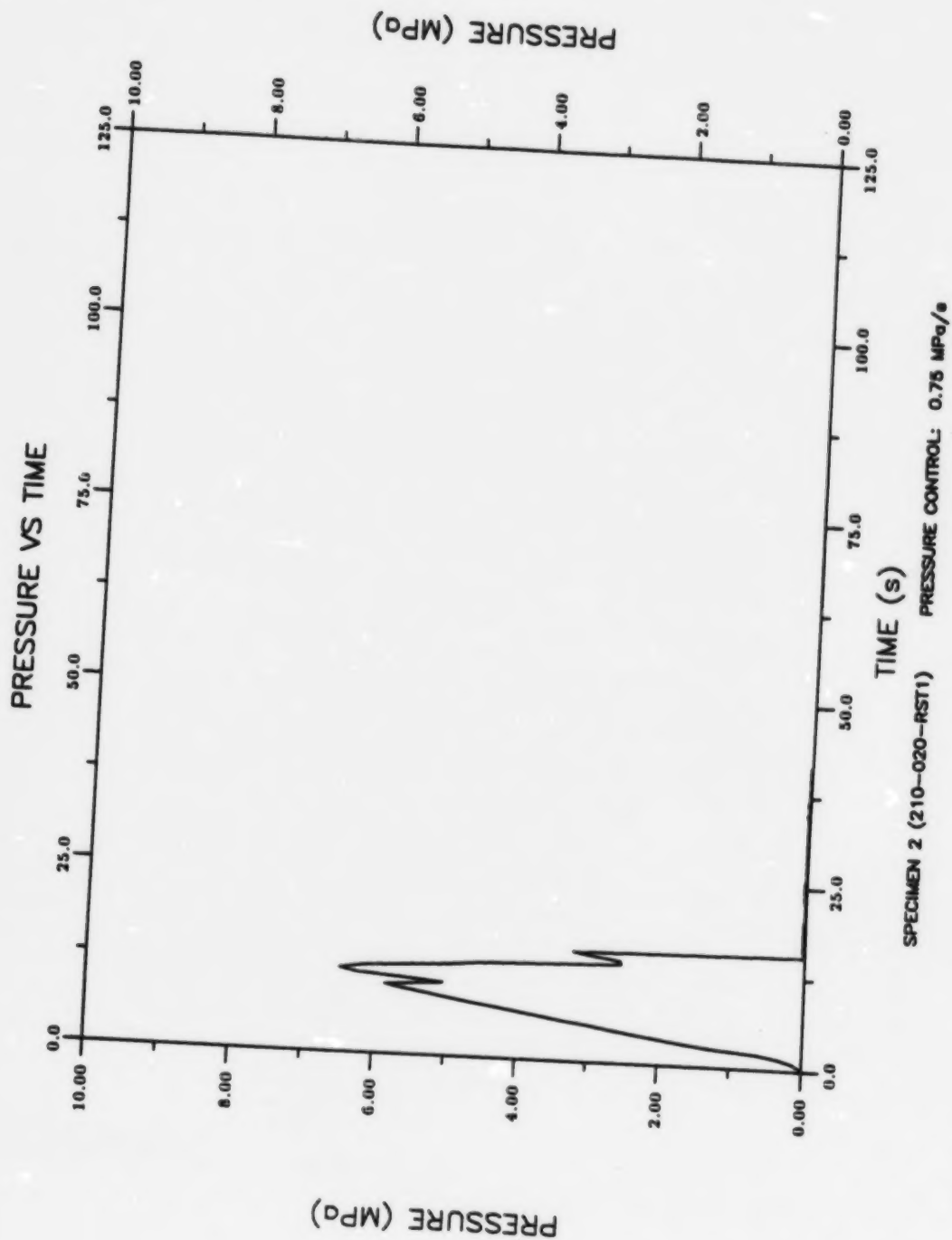


Figure 29. Pressure-time record for the test conducted on Specimen 2 at a pressure rate of 0.75 MPa/s.

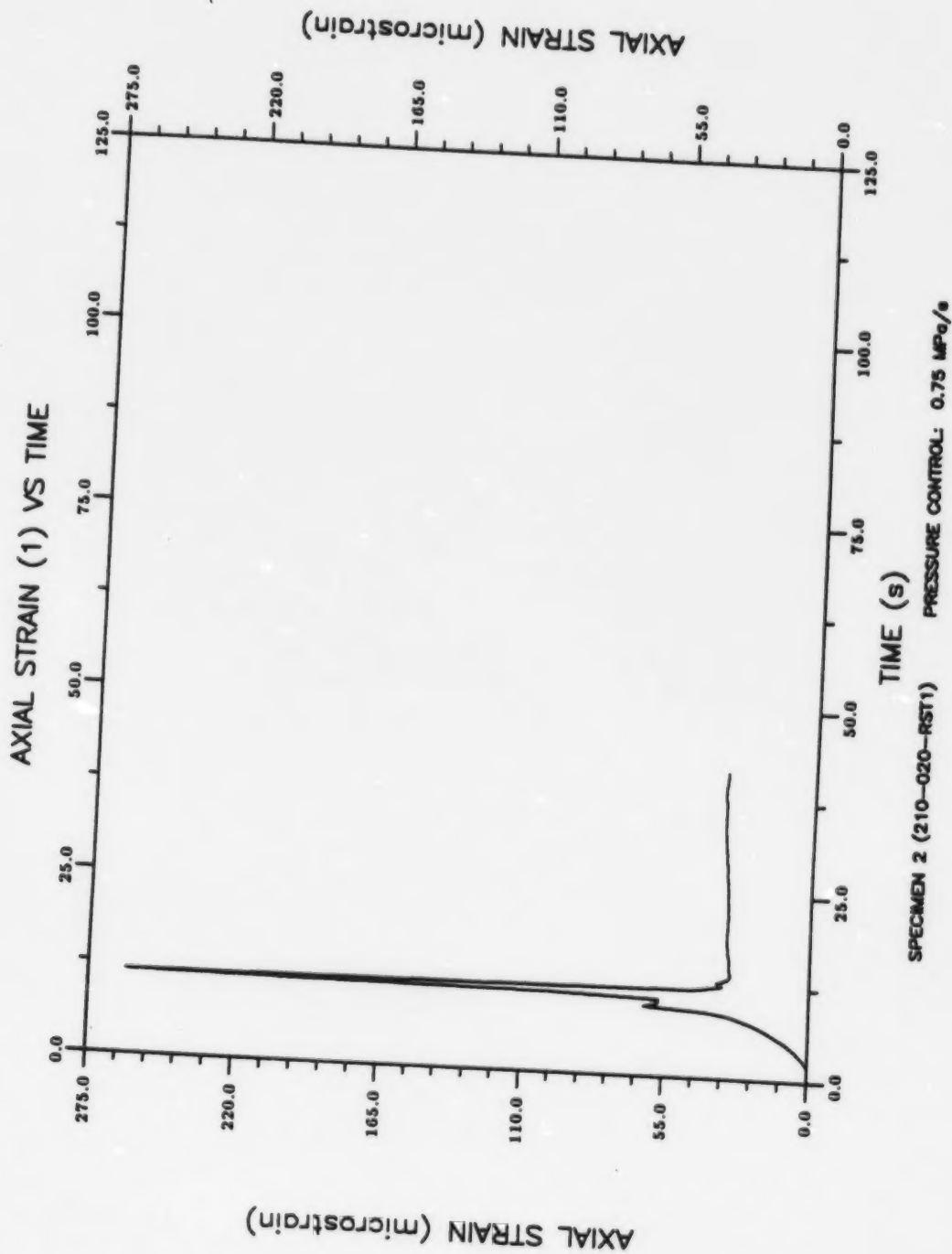


Figure 30. Strain-time record of axial strain No. 1 for the test conducted on Specimen 2 at a pressure rate of 0.75 MPa/s.

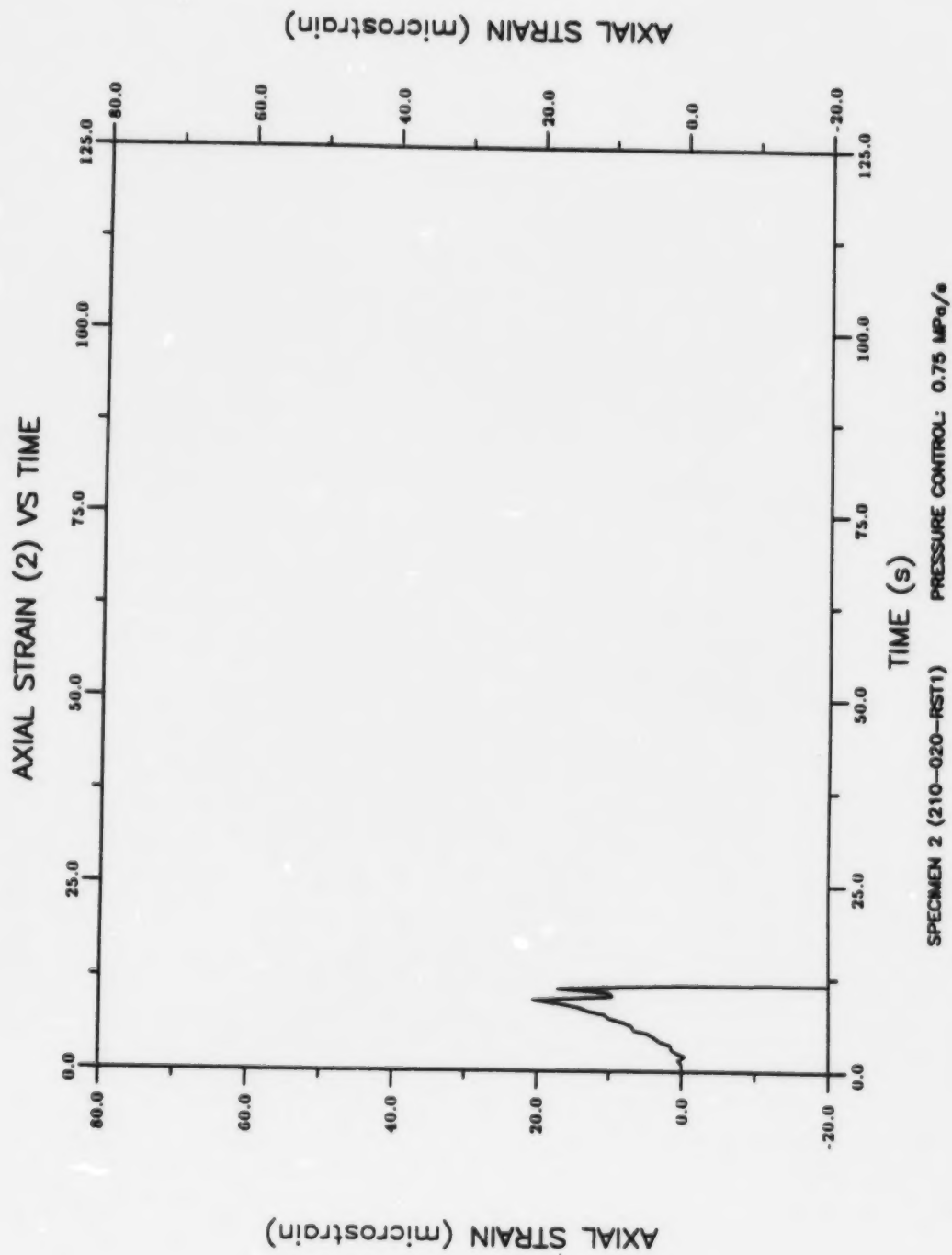


Figure 31. Strain-time record of axial strain No. 2 for the test conducted on Specimen 2 at a pressure rate of 0.75 MPa/s.

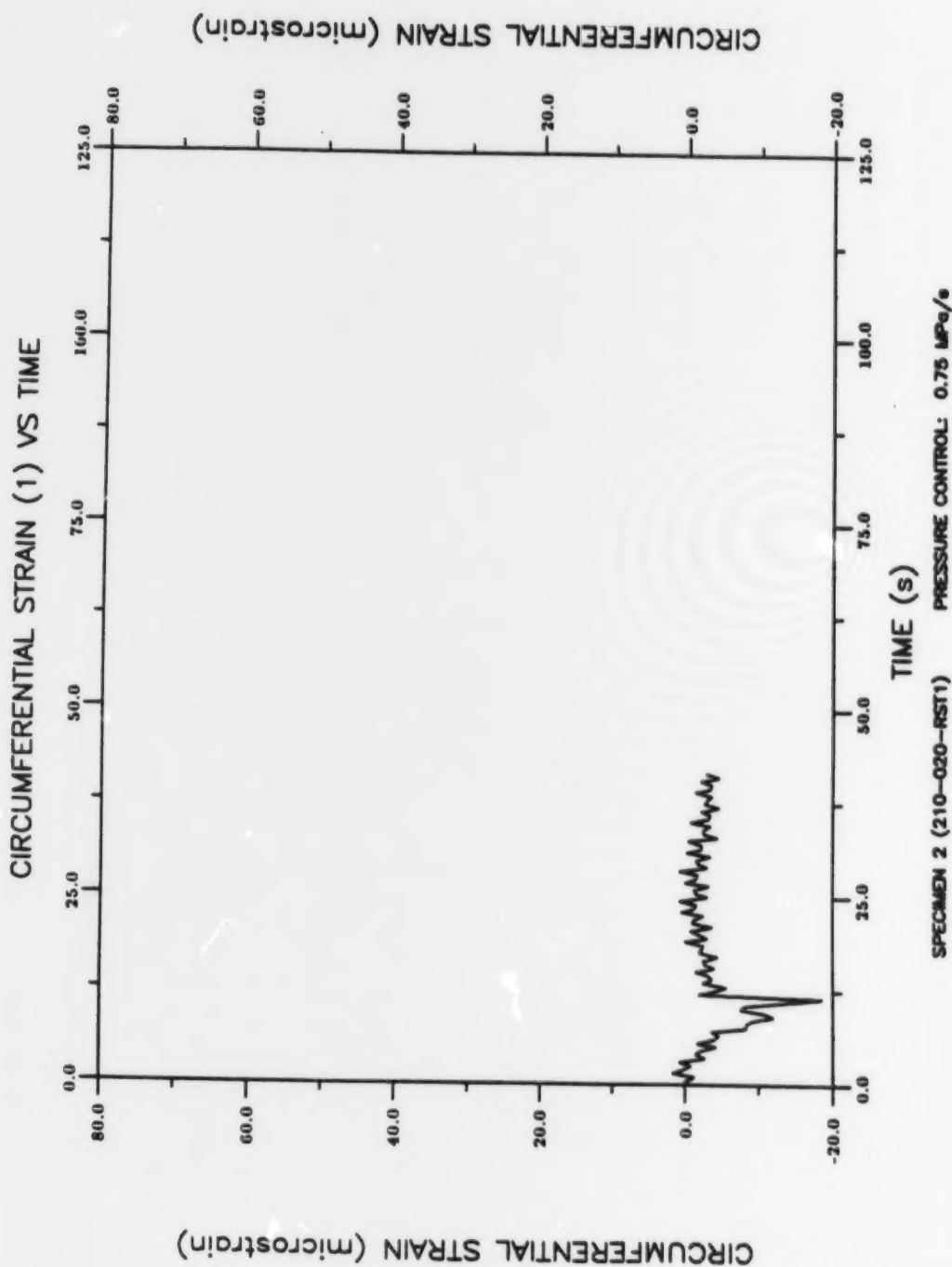


Figure 32. Strain-time record of circumferential strain No. 1 for the test conducted on Specimen 2 at a pressure rate of 0.75 MPa/s.

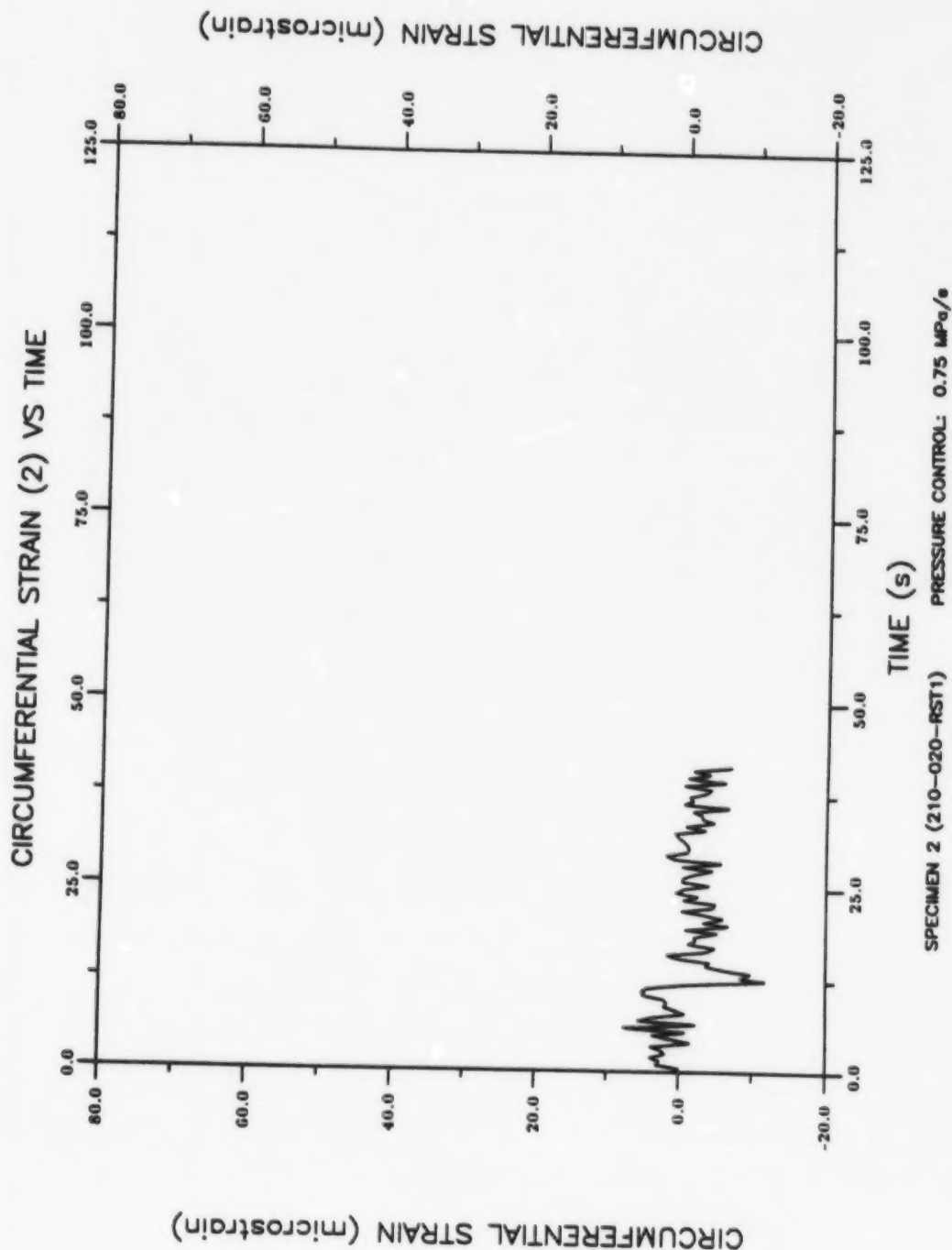


Figure 33. Strain-time record of circumferential strain No. 2 for the test conducted on Specimen 2 at a pressure rate of 0.75 MPa/s.

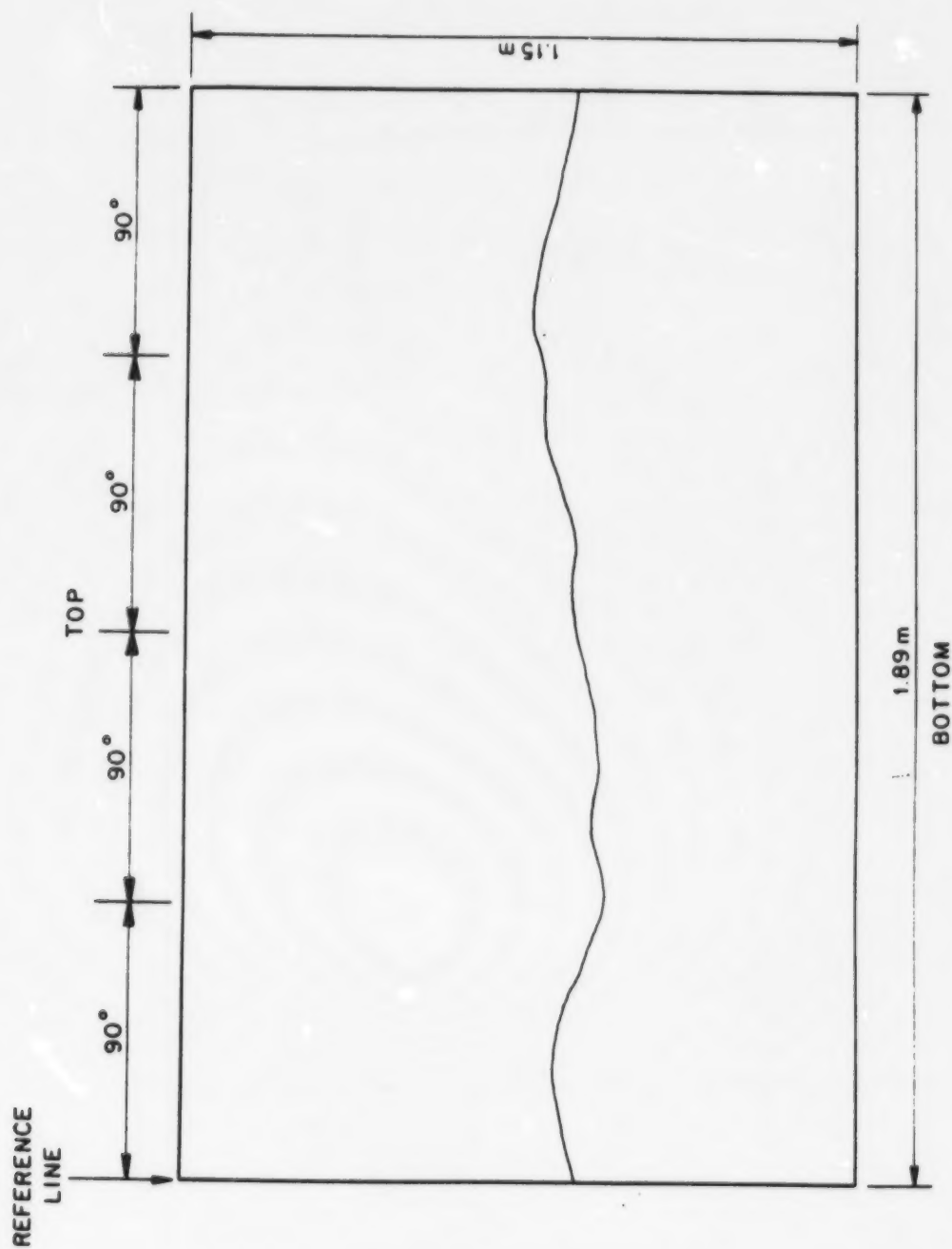


Figure 34. Trace of Hydrofracture on the surface of Specimen 2.

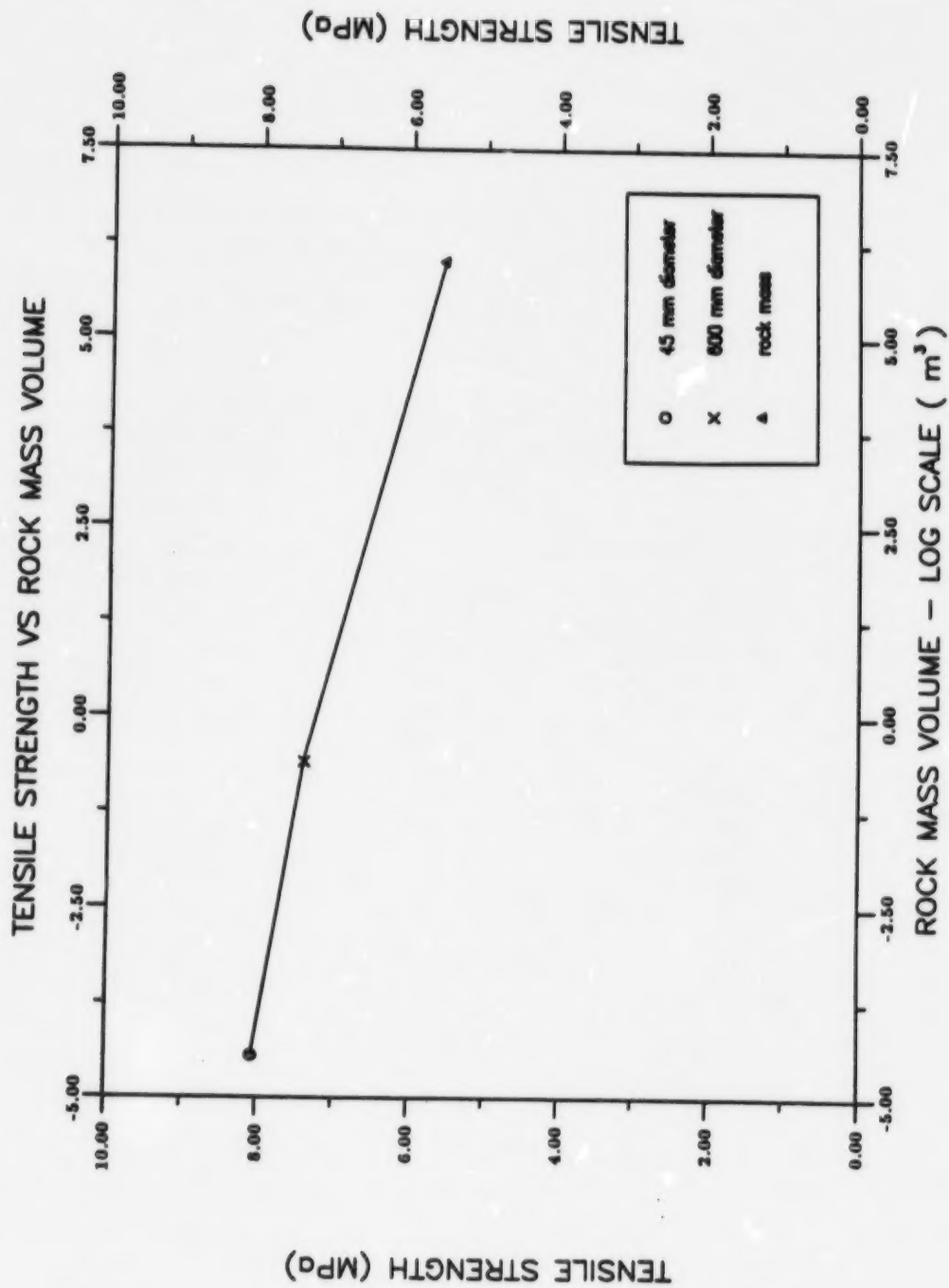


Figure 35. Plot of tensile strength versus rock mass volume.